SUSY Searches at D0

OUTLINE

- Introduction
- Searches for gaugino pair production
- Searches for squark/gluino production
- 3rd generation squarks (sbottom, stop)
- Selected SUSY Higgs search results
- More "Exotic" SUSY searches
  - RPV, HV, …
- Summary

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On behalf of the D0 Collaboration

LHC @ BNL Workshop, January 10/2011

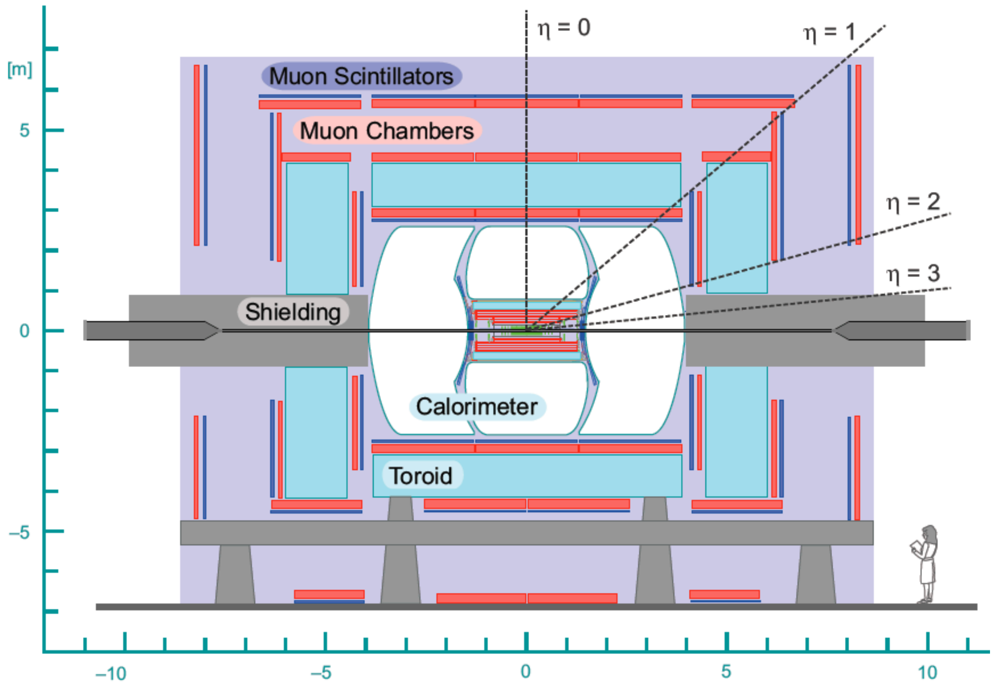
Introduction

- In Run II, D0 has published > 30 papers on searches for SUSY
  - So far, no SUSY discovery
  - Significant limits set on a variety of SUSY particles and SUSY model implementations
- Lack of SUSY discovery (at LEP, Tevatron, …) has already initiated:
  - Extensive discussion about need for "fine-tuning" of MSSM
  - Generation of new ideas (and models) about how to "hide" SUSY so far
- In this talk, I will focus on relatively recent D0 SUSY results

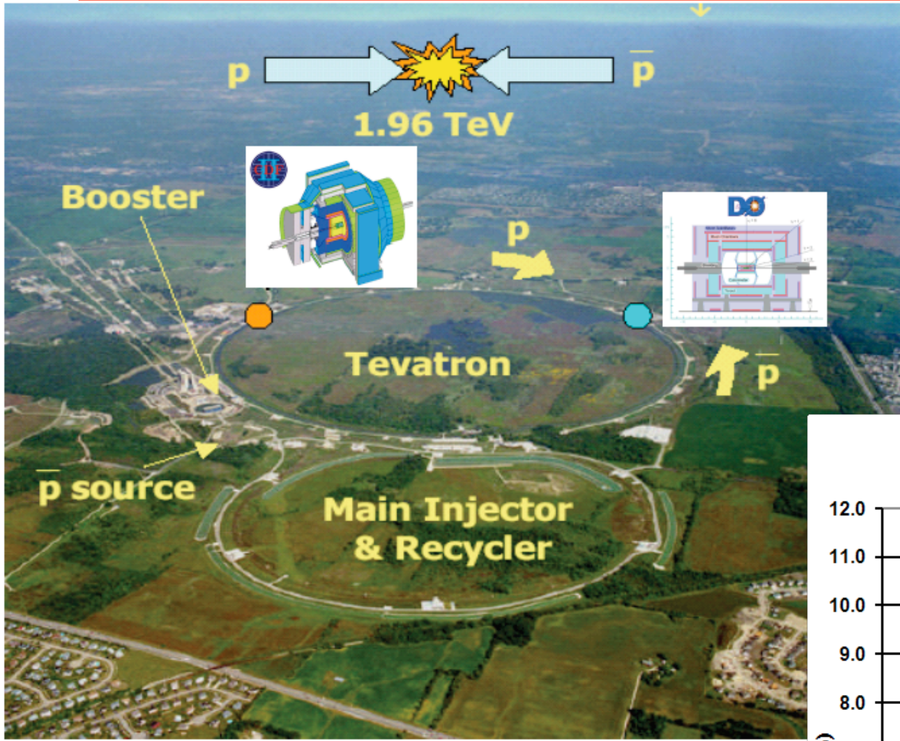
The D0 Experiment

- D0 Collaboration includes ~ 500 physicists from 86 institutions in 19 countries

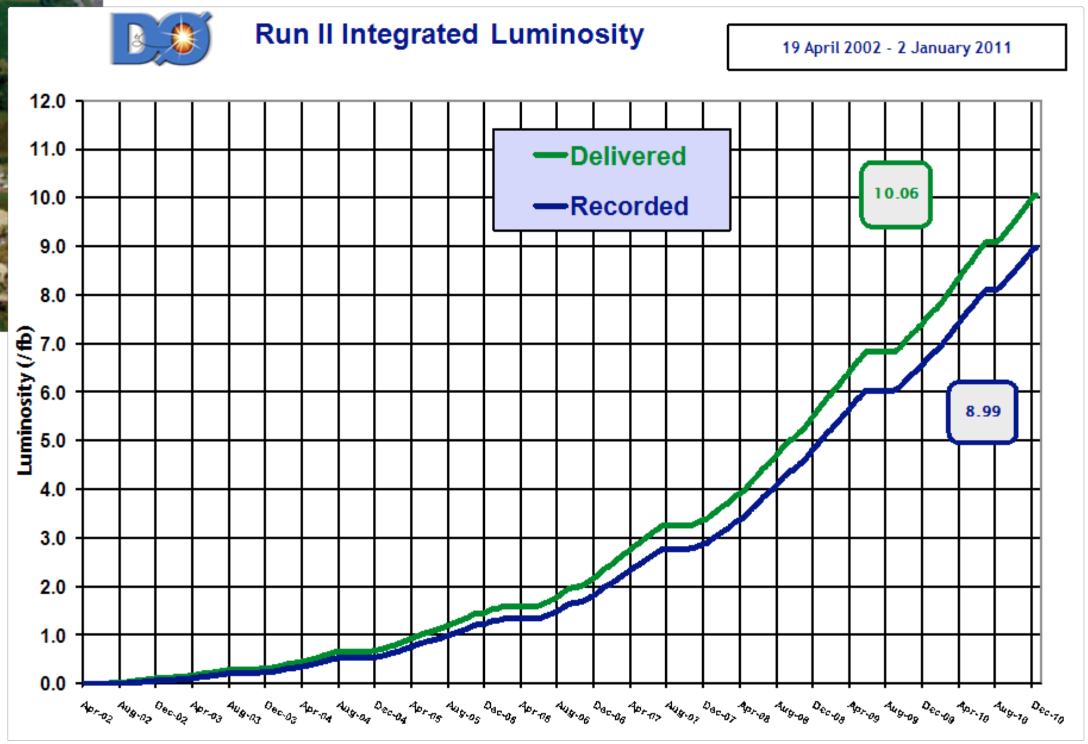
- D0 detector is a well understood, multi-purpose detector, designed with flexibility to search for BSM physics in a variety of final states and signatures



The Fermilab Tevatron



- **proton-antiproton collisions with center-of-mass energy 1.96 TeV**



Run II Integrated Luminosity

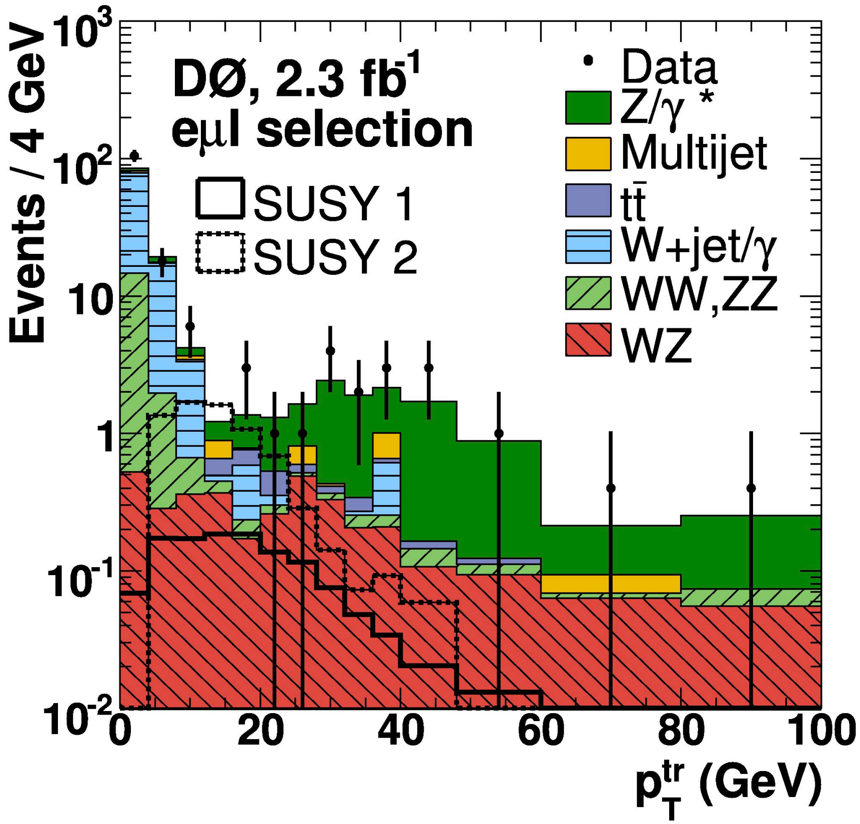
Delivered = 10 fb^{-1}

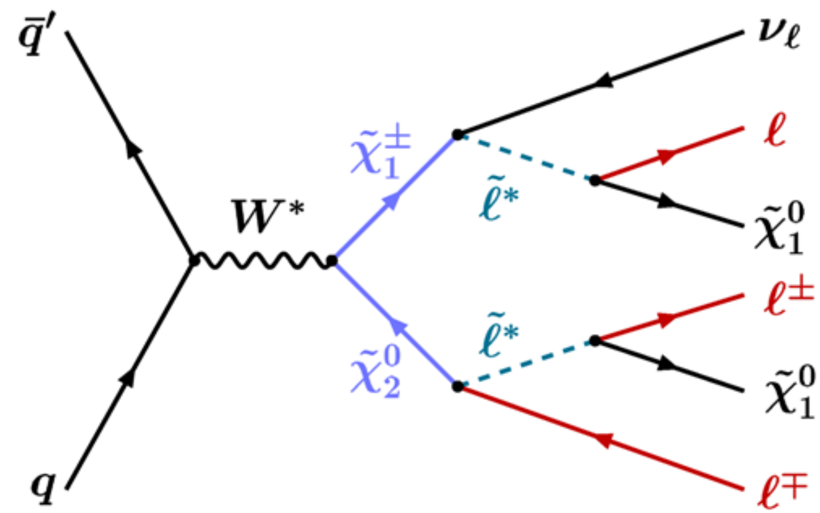
Recorded = 9 fb^{-1}

SUSY in Trileptons

2.3 fb^{-1} [PLB 680 (2009) 34]

- "Classic" SUSY signature of 3 isolated leptons + MET, with very little SM bkgnd





- Main experimental challenge is to achieve high efficiency for this low σ×BR process, particularly given the soft p_T spectrum of the third leading lepton

- Search strategies:
  - 2 leptons (ee, μμ, eμ) + isolated trk (l)
  - μτ + isolated trk (l)
  - μτ + τ

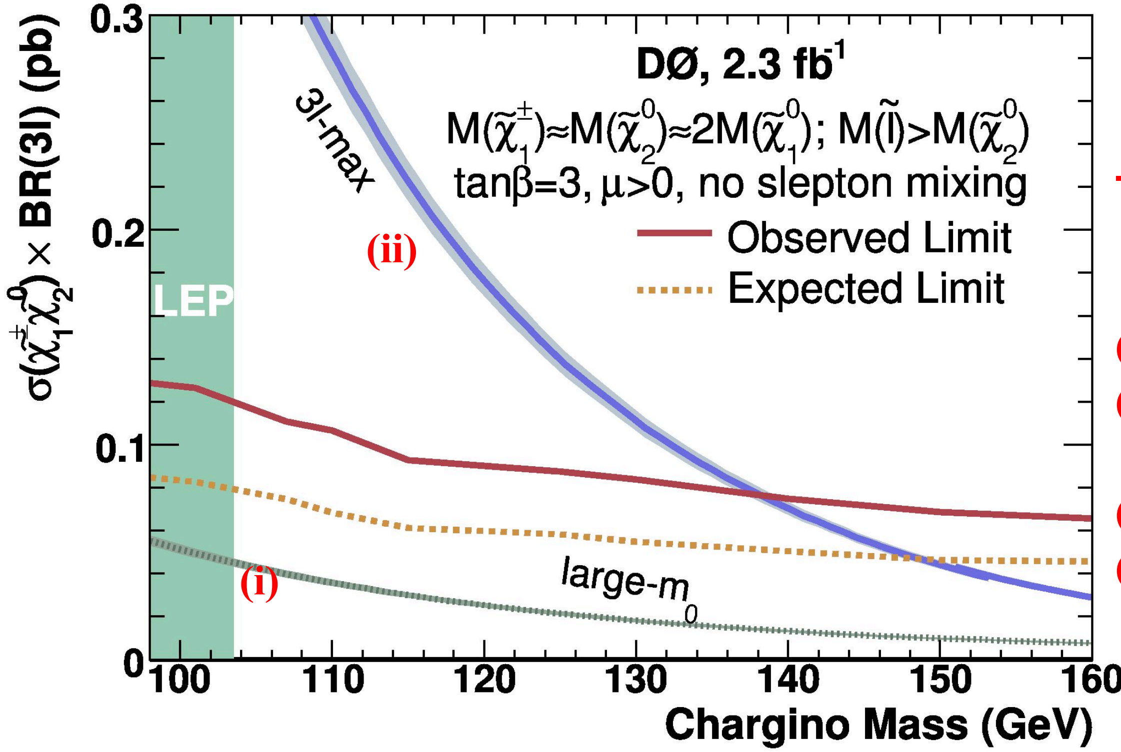
  (τ reconstructed from 1 trk + CALO cluster)

Trilepton Results

- Good agreement between data and SM background expectation ⇒ set limits

(1) On σ×BR as a function of chargino mass

- assuming typical mSUGRA mass relations: $m(\chi_1^\pm) \approx m(\chi_2^0) \approx 2m(\chi_1^0)$



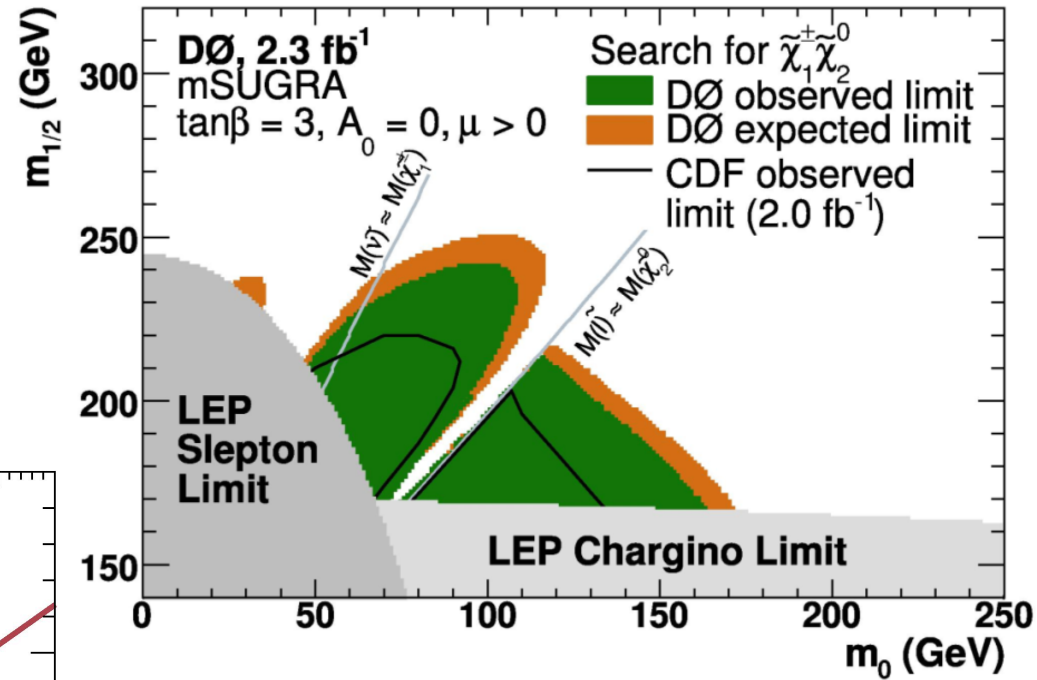
- in 2 cases of 3-body gaugino decays, where:

(i) sleptons much heavier than $\chi^\pm$ ("large-m_0")

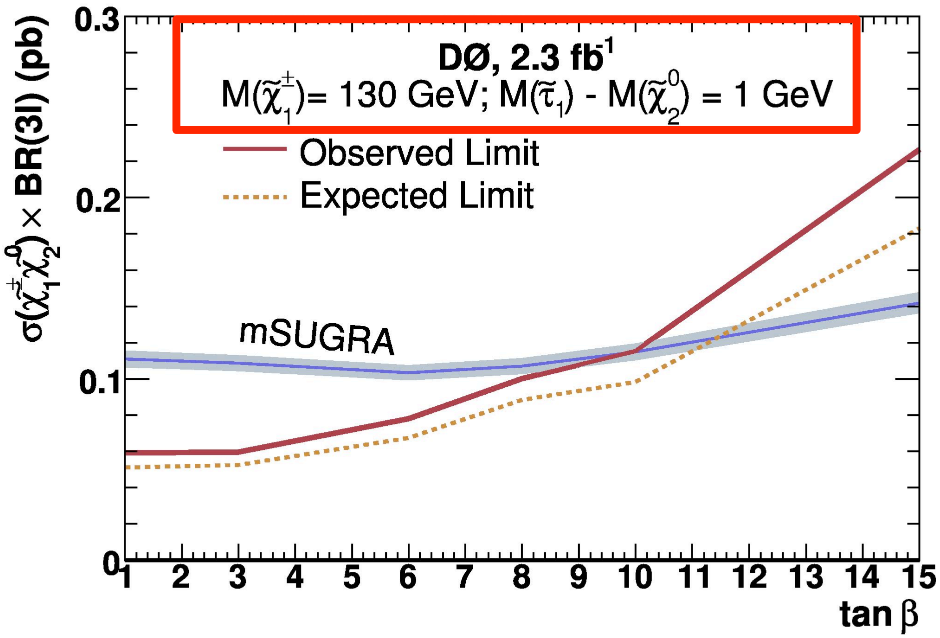
(ii) slepton masses just above $\chi^\pm$ mass ("3l-max"), in which case

$m(\chi^\pm) > 138$ GeV (@ 95% CL)

Trilepton Results (cont'd)



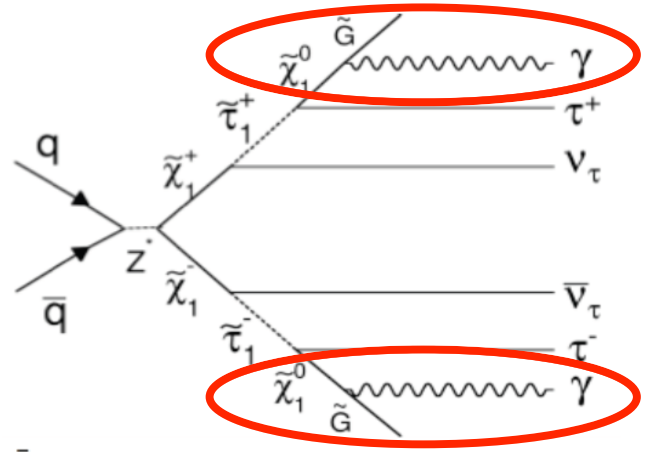
(2) in mSUGRA plane ($m_{1/2}$ vs m_0)
- consider values $\tan\beta=3$, $A_0=0$, $\mu > 0$
- both 2- and 3-body decays allowed



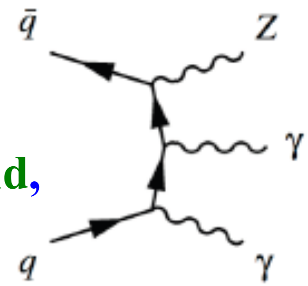
(3) Examine $\tan\beta$ dependence
- BR to τ final states increases at large $\tan\beta$
- can exclude $m(\chi^\pm)$ = 130 GeV for values of $\tan\beta$ up to 9.6

GMSB in $\gamma\gamma$ + MET

6.3 fb^{-1} [PRL 105 (2010) 221802]



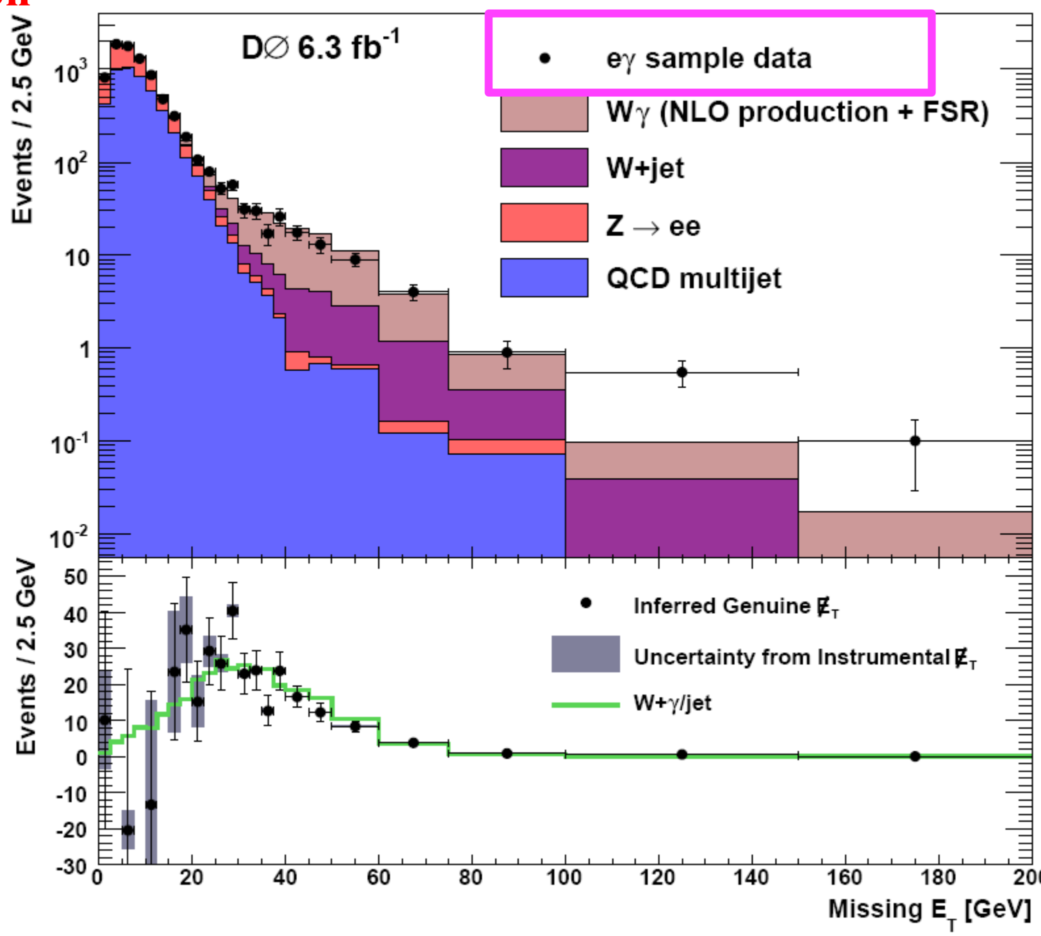
- In Gauge Mediated SUSY Breaking (GMSB) models, Gravitino is LSP and very light (~ keV)
- Gaugino pair (and some slepton pair) production, with cascade decays to NLSP
- If NLSP is neutralino, it decays via $\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma$ giving rise to $\gamma\gamma$ + MET final state



- This final state has a very small irreducible SM bkgnd, mostly from W/Z + $\gamma\gamma$ (which we model with MC)
- Main experimental challenge is to control instrumental backgrounds, which must be estimated with data
- An additional issue is to associate diphoton with correct primary vertex among the typically ~ 10 interactions per b.c. (spread along beamline with σ_z ~ 20 cm)
  - Use "pointing" capability of CALO + central preshower

GMSB in γγ + MET (cont'd)

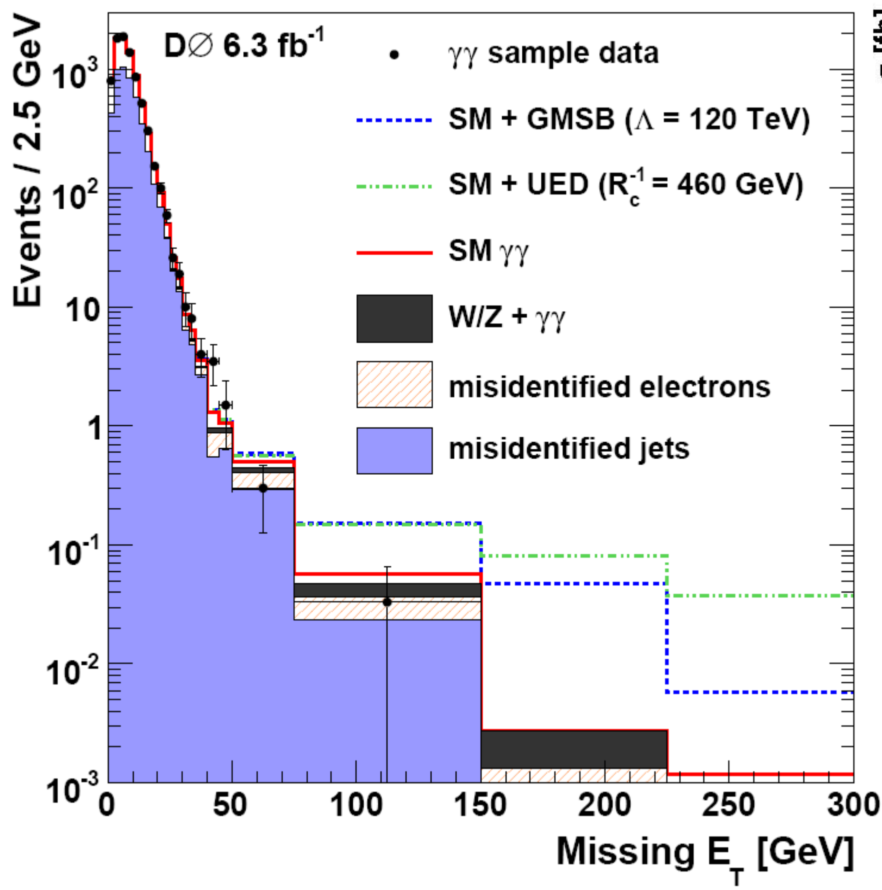
- Instrumental bkgnds without real MET
  - SM γγ (shape modeled in data by ee)
  - γ+jet and multijet events, with jet(s) faking photon(s) (shape from data)
  - Normalized in low MET region

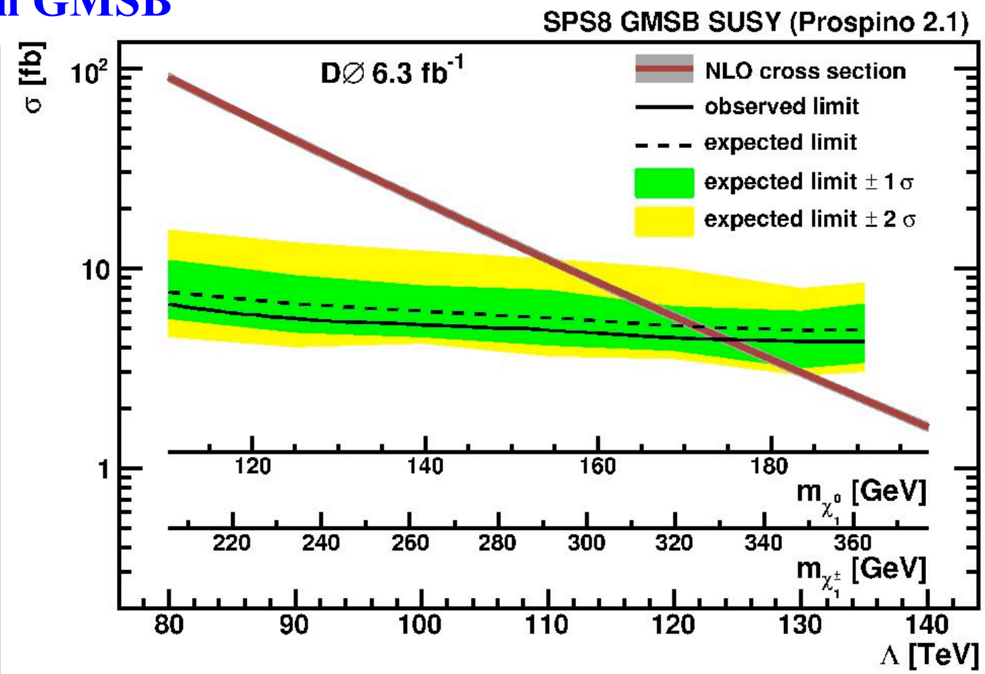


- Instrumental bkgnds with genuine MET
  - W+γ and W+jet with e→γ misidentification
  - Measured in data using an e+γ control sample

GMSB in γγ + MET Results

- No excess seen at high MET ⇒ limits on GMSB





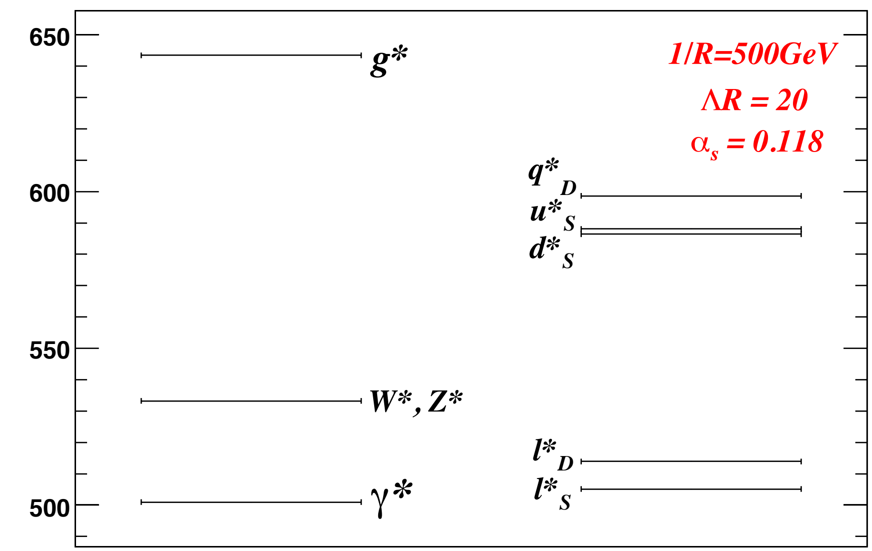
$$\Lambda < 124 \text{ TeV}$$
$$m_{\chi_1^\pm} < 332 \text{ GeV}$$
$$m_{\chi_1^0} < 175 \text{ GeV}$$

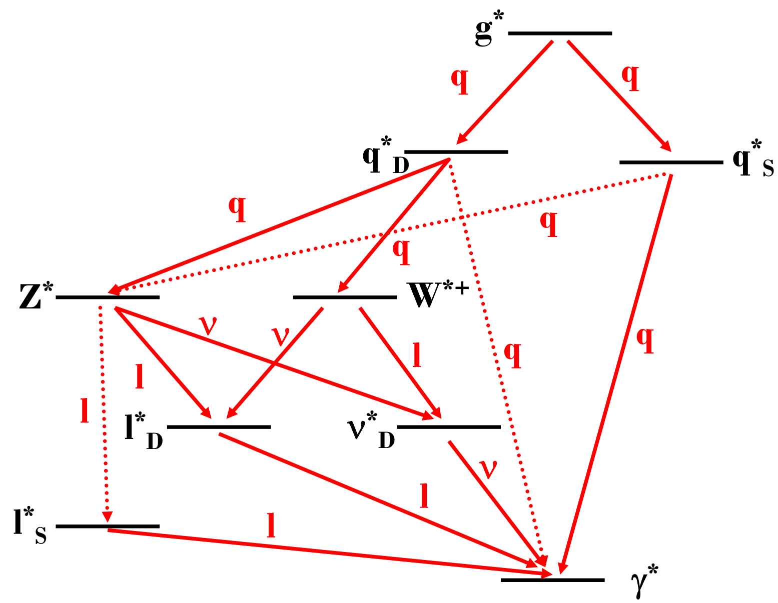
- Set 95% CL exclusions within SPS8 benchmark: (Λ free, $M_{mess} = 2\Lambda$, $N_{mess} = 1$, $\tan\beta = 15$, $\mu>0$)

UED Interpretation of γγ + MET Results

- Result also interpreted within a specific Universal Extra Dimension model, with a single UED with compactification radius R (~ 1/TeV)
  - Predict KK tower for each SM particle (with levels separated by ~ 1/R)
- Strong production of KK quark and/or gluon pairs, followed by cascade decay to LKP (which, after radiative mass splittings, is lightest γ*)

Pythia 6.4.20 UED - First level KK mass spectrum [GeV]

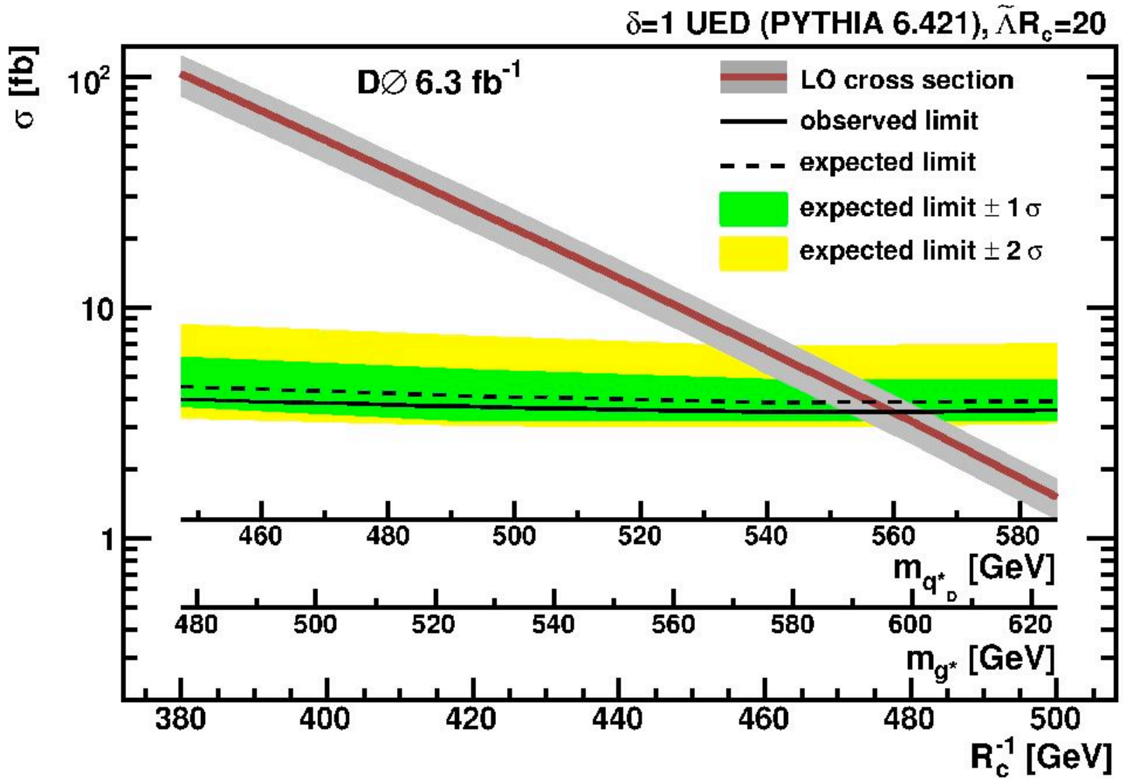




- If embed single UED in space with N large (~ 1/eV) extra dim's accessible only to gravity, induce gravity-mediated decays of LKP via γ* → γ G
  - Final state is γγ + MET

UED Interpretation of γγ + MET Results (cont'd)

- Re-interpret lack of excess of γγ events at high MET to set the first experimental limit on this UED model



- D0 result (6.3 fb^{-1}) is $R^{-1} > 477$ GeV (@95% CL)

(NEW!) ATLAS UED Result

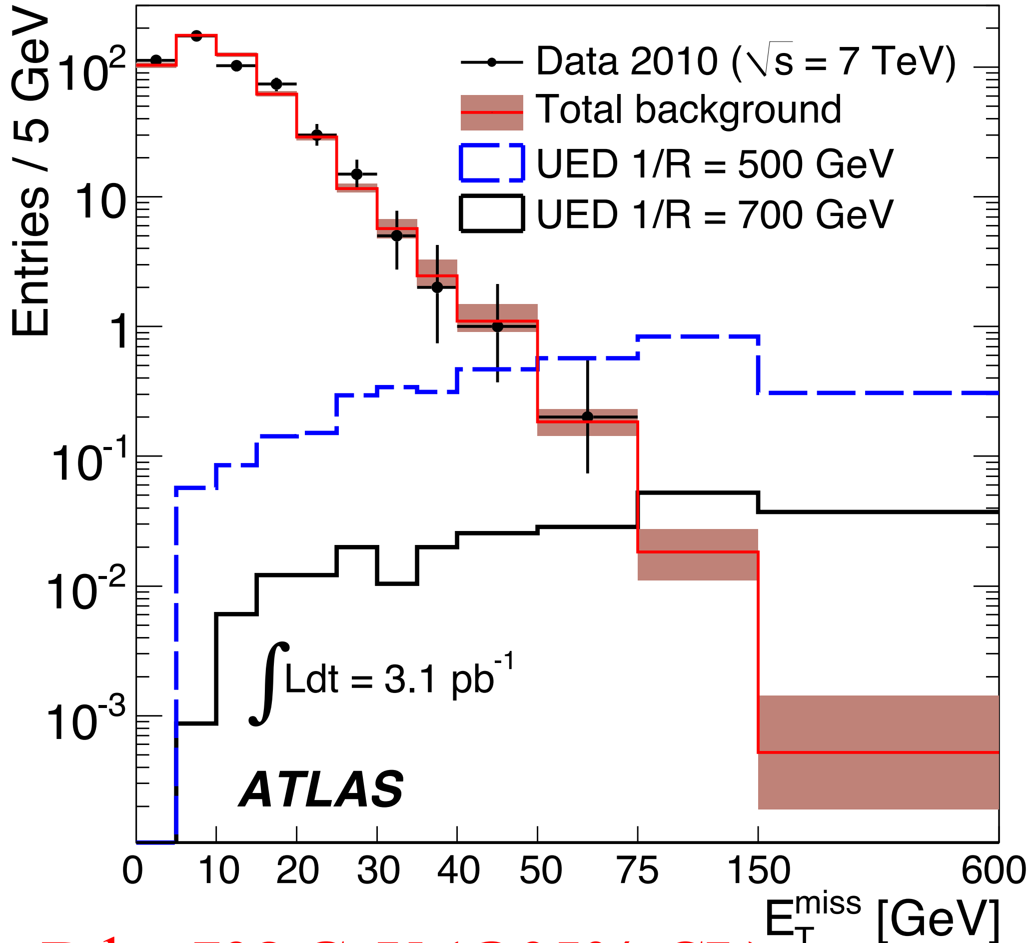
- **ATLAS has recently submitted for publication a very similar γγ + MET analysis**

[arXiv:1012.4272, submitted to PRL]

- **Uses the first 3.1 pb^{-1} of their 2010 data (7 TeV pp collisions)**

- **Result interpreted in same UED benchmark as used in D0 result**

(GMSB is not yet included since it requires more integ. lumi. to be competitive)



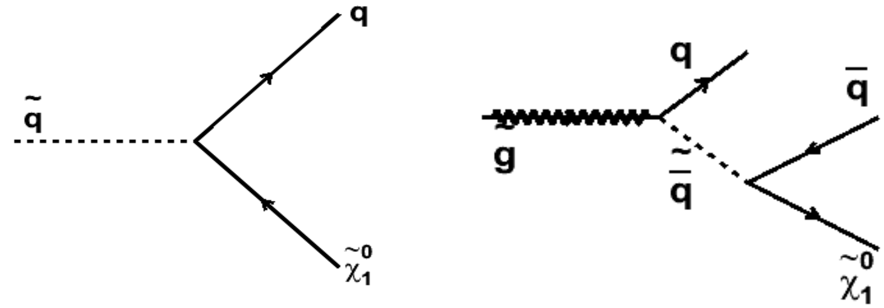
- **ATLAS result (3.1 pb^{-1}) is R^{-1} > 728 GeV (@95% CL)**

cf. D0 result (6.3 fb^{-1}) of R^{-1} > 477 GeV

Squark/gluino production

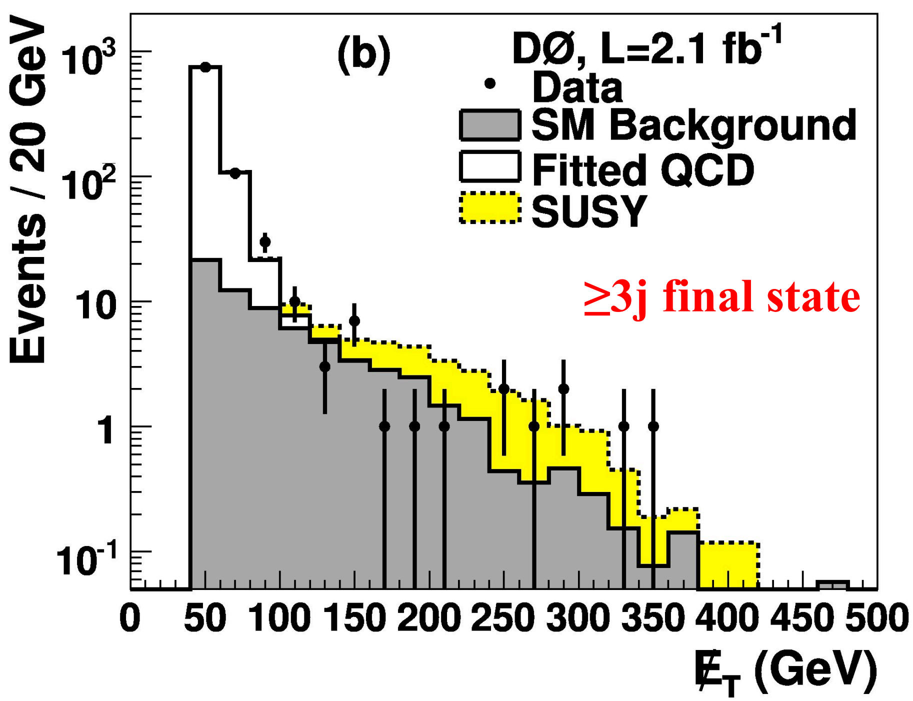
2.1 fb^{-1} [PLB 660 (2008) 449]

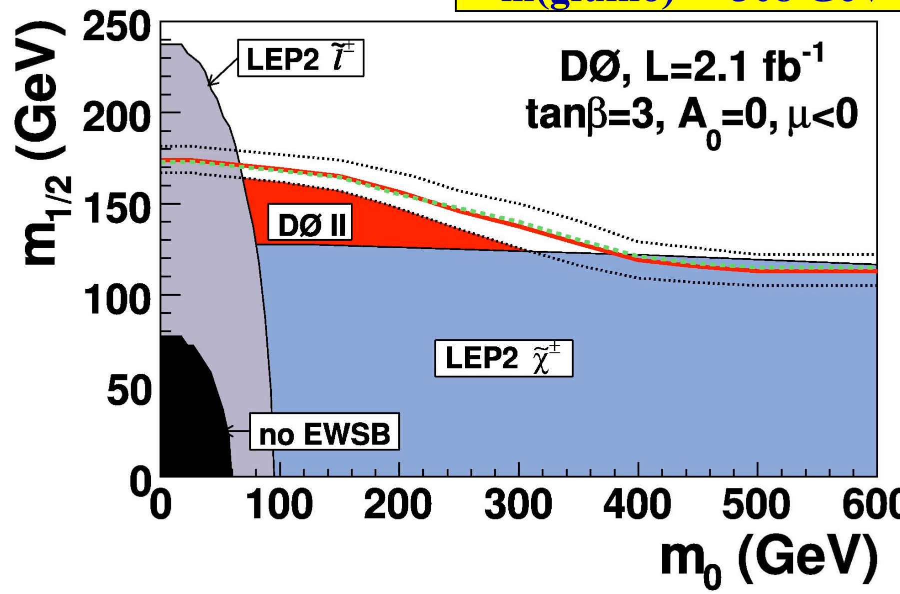
- Pair production via strong interaction, followed by cascade decays to LSP
  - Final state is multijets + MET
  - Searches performed separately in 2j ($\tilde{q}\tilde{q}$), ≥3j ($\tilde{q}\tilde{g}$), ≥4j ($\tilde{g}\tilde{g}$) states



- No excess seen ⇒

m(squark) > 379 GeV
m(gluino) > 308 GeV





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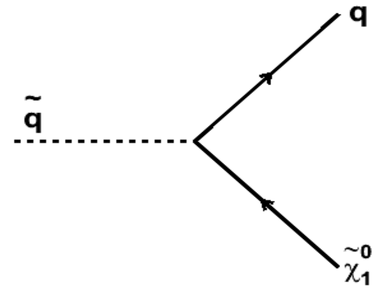
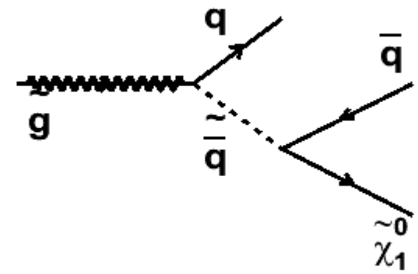
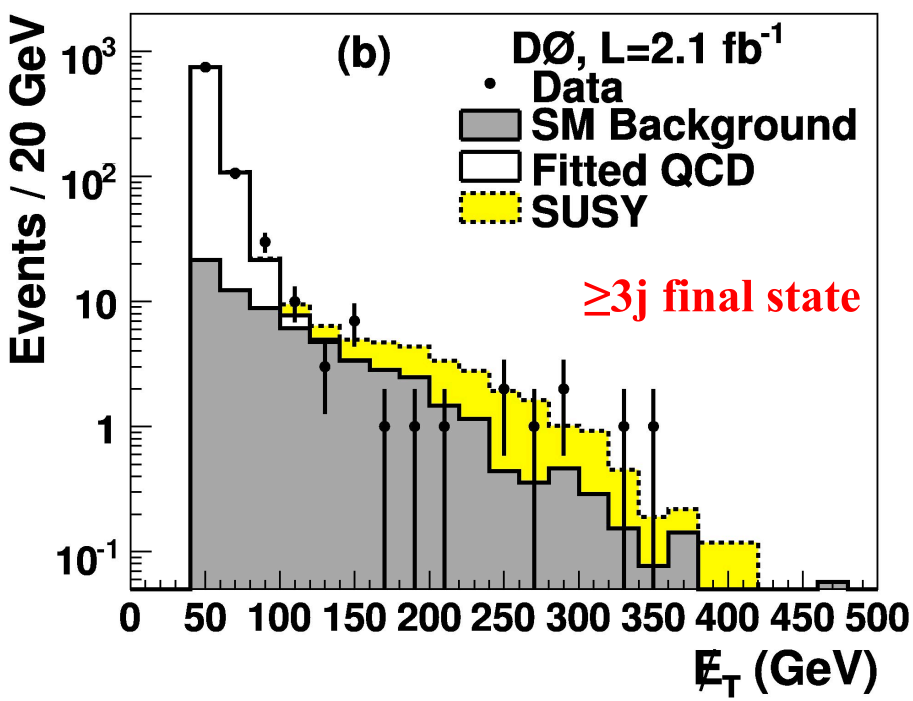
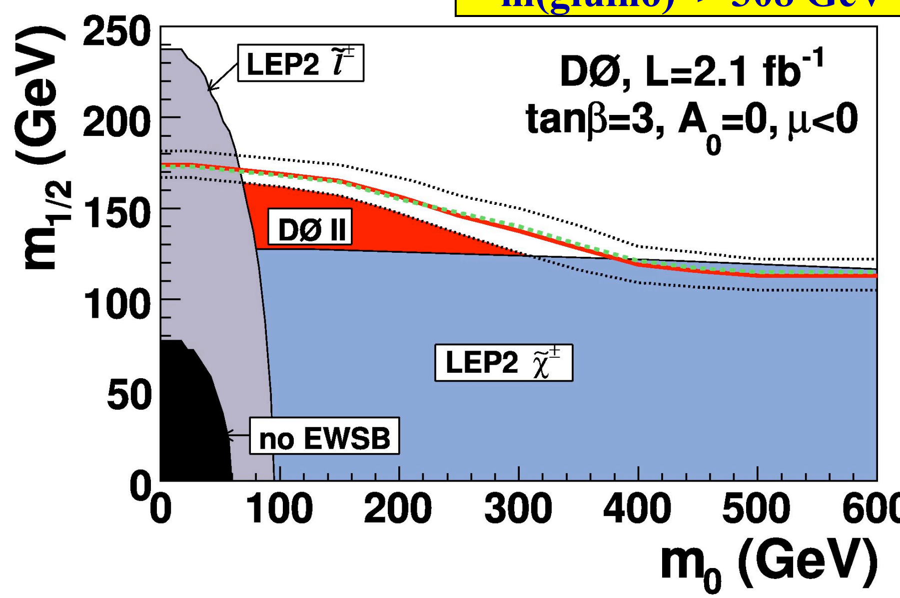






- No excess seen ⇒ m(squark) > 379 GeV
  m(gluino) > 308 GeV

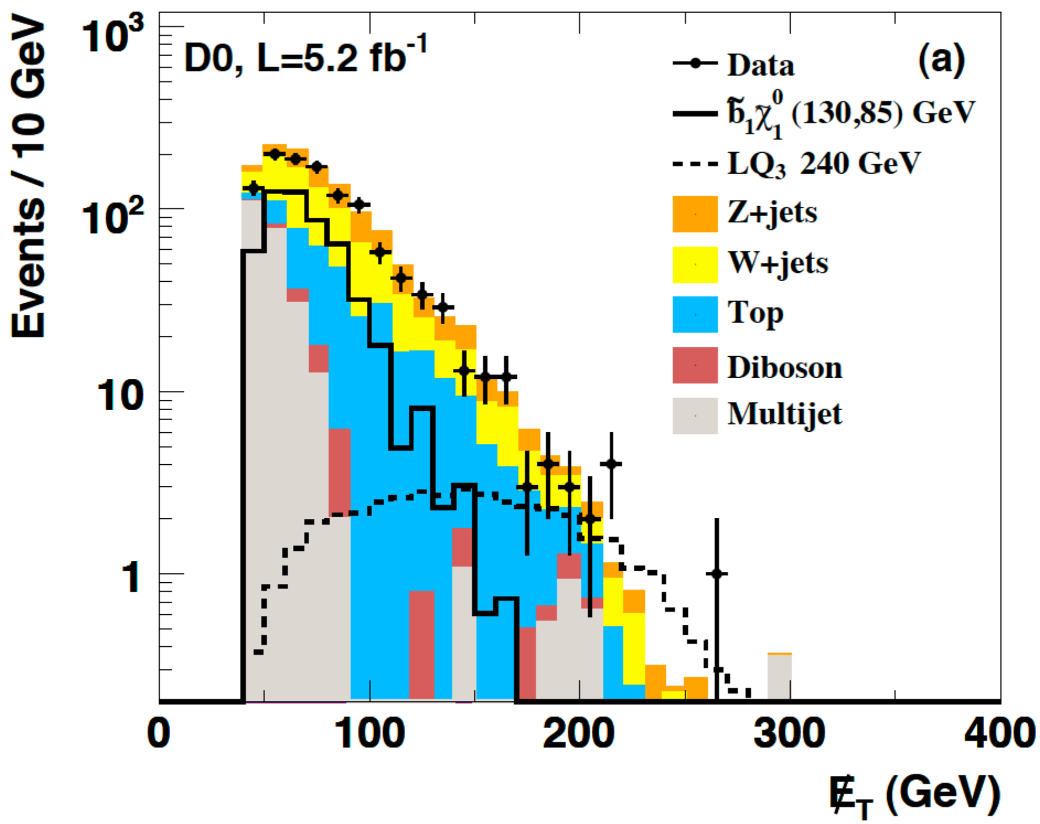


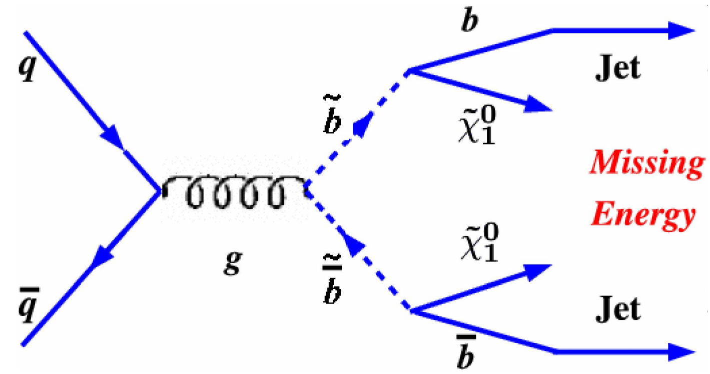
- Limits surpassed by CMS Preliminary results with 35 pb^{-1} shown Dec. 17/2010

Sbottom search

5.2 fb^{-1} [PLB 693 (2010) 95]

- Due to mixing in 3rd generation, $\tilde{b}_1$ could be light
  - Strong production of sbottom pairs
  - Assume $BR(\tilde{b}_1 \to b\chi_1^0) = 100\%$





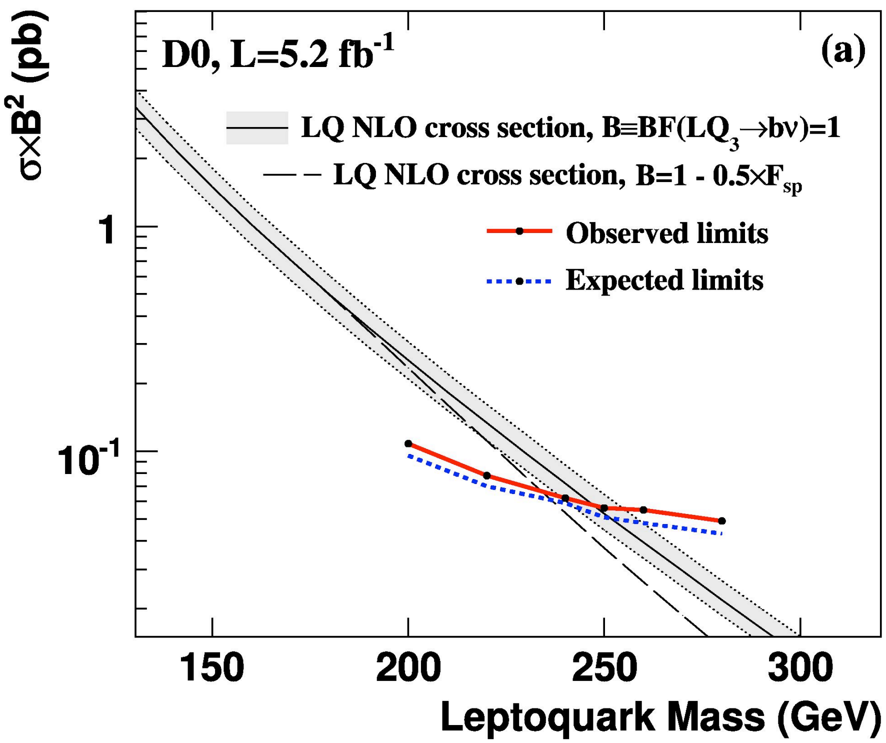
- Signal yields 2 bjets + MET $\Rightarrow$ challenging final state!

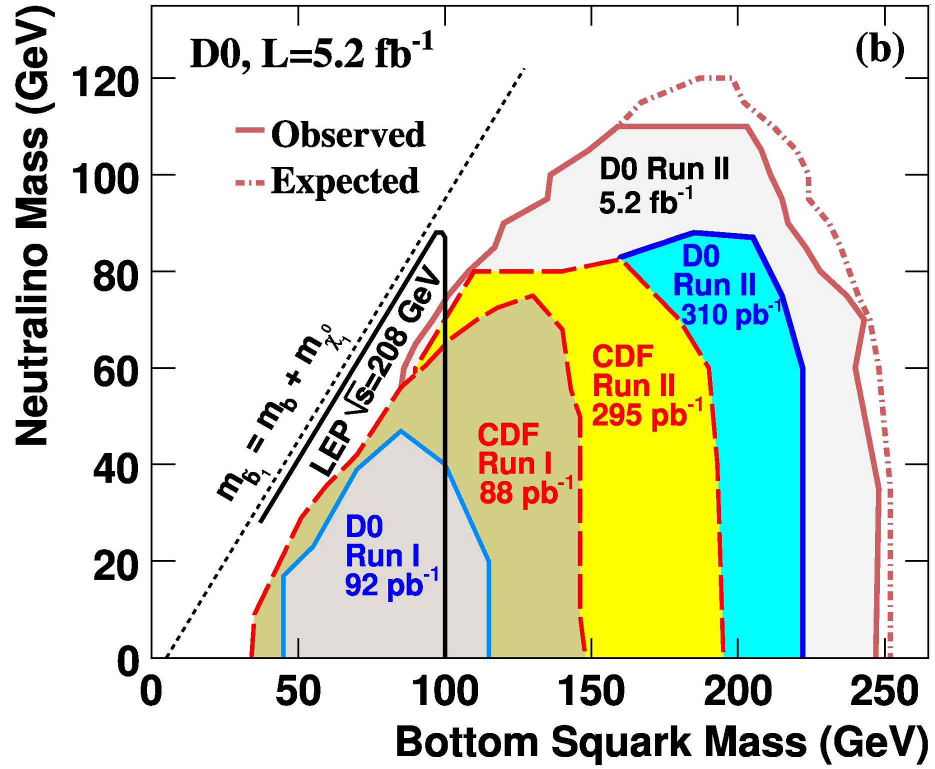
- After b-tagging and cuts to reduce events with MET mismeasurements, major backgrounds are due to
  - W/Z + heavy flavor
  - top

Sbottom search results

- **SUSY exclusions (@ 95% CL):**

$$m_{\tilde{b}_1} < 247 \text{ GeV for } m_{\chi_1^0} = 0$$
$$\text{For } m_{\chi_1^0} = 110 \text{ GeV}, \quad 160 < m_{\tilde{b}_1} < 200 \text{ GeV}$$





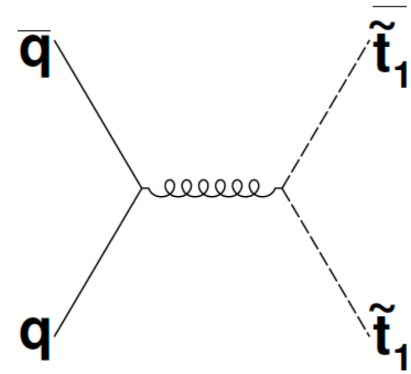
- **3rd generation LQ interpretation: exclude (@ 95% CL)**

$m_{LQ_3} < 247$ GeV for 100% $LQ_3 \to b\nu$

$m_{LQ_3} < 238$ GeV for equal couplings $LQ_3 \to b\nu, t\tau$

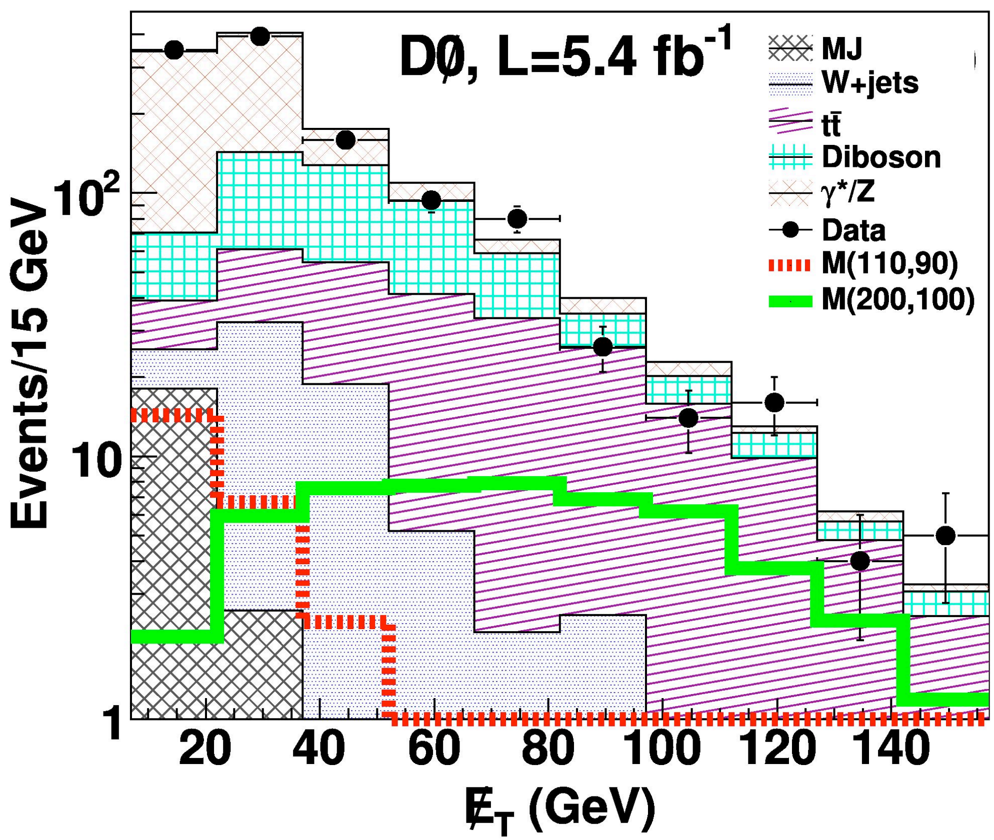
Stop searches

- Due to mixing in 3rd generation, $\tilde{t}_1$ could be light
  - Strong production of stop pairs
  - Stop decay (ie. final state) depends on mass hierarchies



- Most recent D0 stop search result:

5.4 fb^{-1} [arXiv:1009.5950, accepted by PLB]



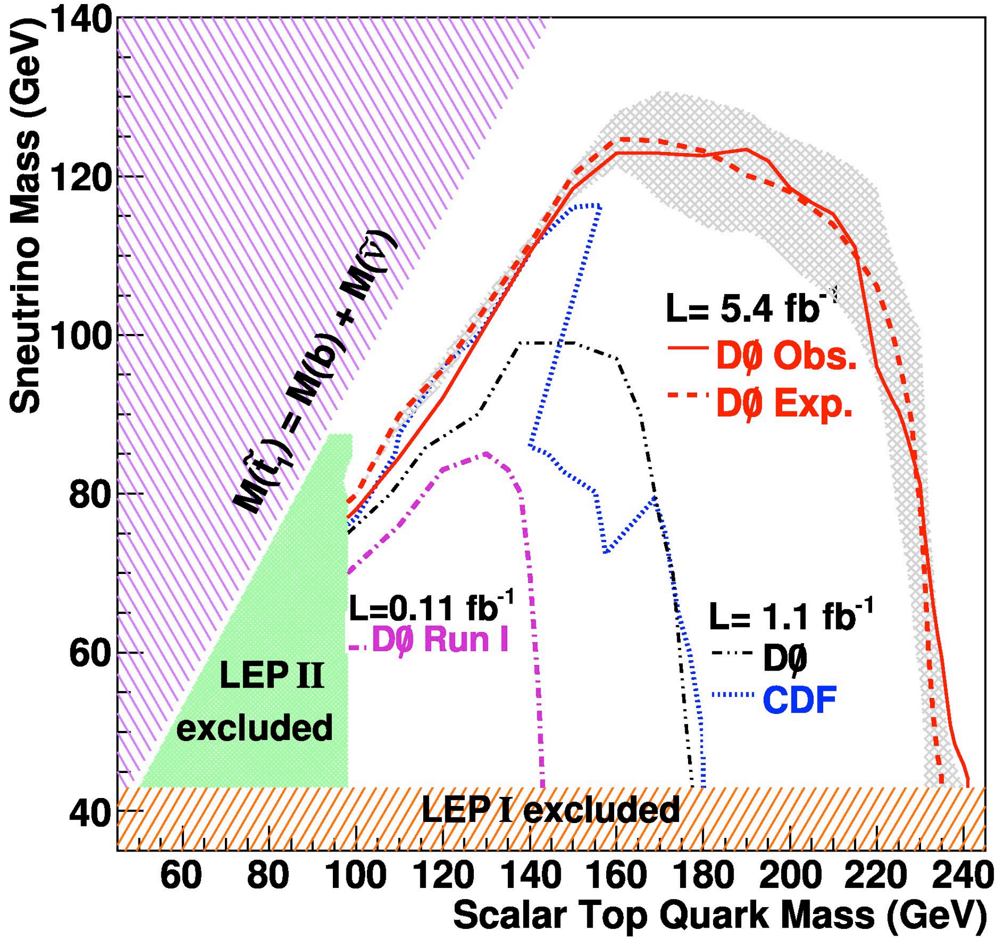
- Assume 3-body stop decay, with

$$BR(\tilde{t}_1 \rightarrow b\ell\tilde{\nu}) = 100\%$$

and sneutrino is either LSP (ie. stable) or decays invisibly via $\tilde{\nu} \rightarrow \nu + \chi_1^0$

- Look in eμ + MET final state
- Main bkgnds are Z→ττ, top and diboson production

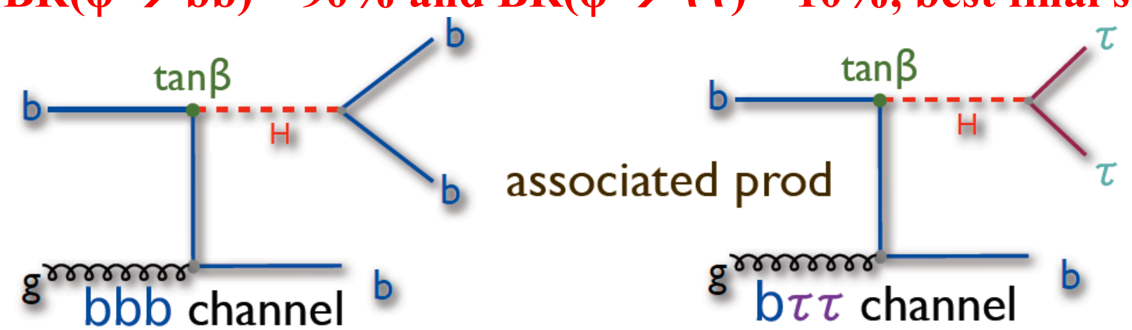
Stop search results



- **Exclude (@ 95% CL), m(stop) < 210 GeV**
  [for sneutrino mass < 110 GeV and m(stop) > m(sneutrino) + 30 GeV]

Selected SUSY Higgs searches

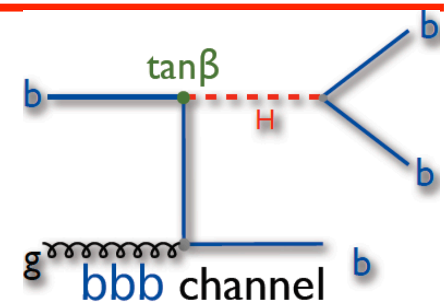
- **MSSM includes 5 physical Higgs bosons**
  - **Neutral scalars h and H and pseudoscalar A (generically referred to as φ)**
  - **Charged Higgs pair $H^{\pm}$**
- **At tree level, Higgs sector described by 2 parameters, typically m_A and tanβ**
  - **Large value of tanβ suggested by m_t/m_b ratio, dark matter, …**
- **In high tanβ regime,**
  - **A is approximately degenerate with either h or H**
  - **Coupling to down-type fermions (eg. b) enhanced by tanβ**
- **Reduce SM background, and get enhancement over SM by a large factor (≈ [2 × $(\tan\beta)^2$]) by searching for φ produced in association with a b (ie. b+φ)**
  - **Given BR(φ → bb) ~ 90% and BR(φ → ττ) ~ 10%, best final states are**



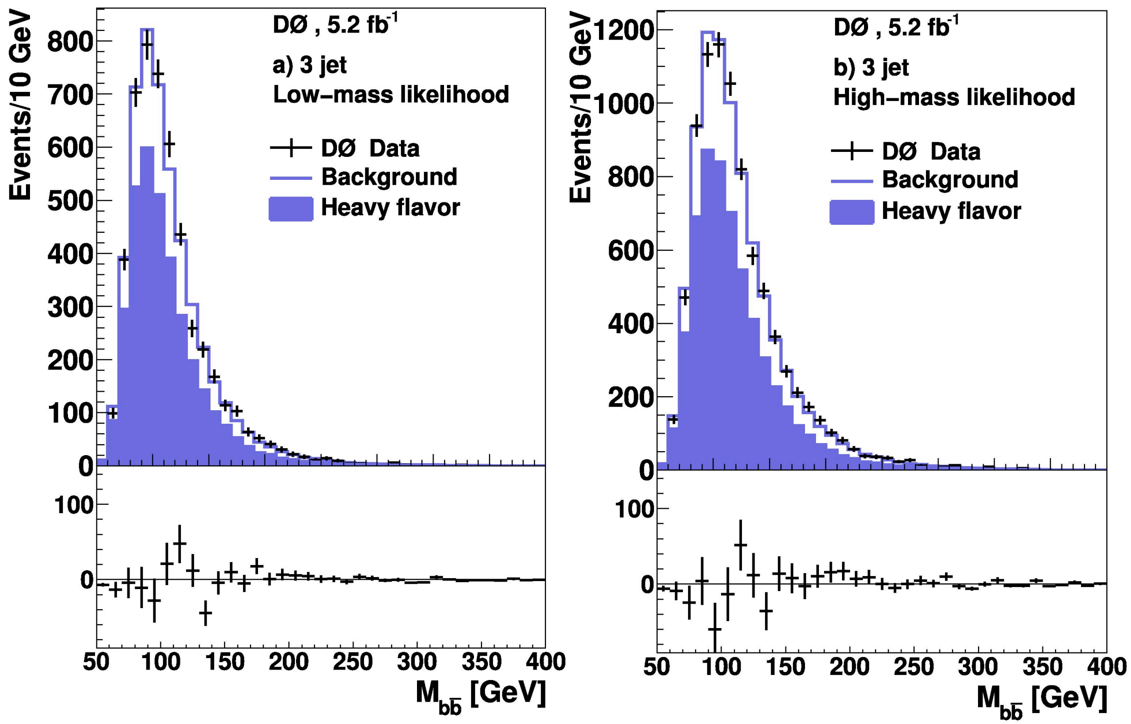
$b+\varphi \rightarrow bbb$

5.2 fb^{-1} [arXiv: 1011.1931, submitted to PLB]

- Require 3 or 4 high p_T jets, with at least 3 btags
  - b-tag performance: 50% effic. with 0.8% mistag rate
  - Events with 2 btags used to help model the bkgnd



- In each event, take dijet with highest scalar summed p_T as Higgs candidate

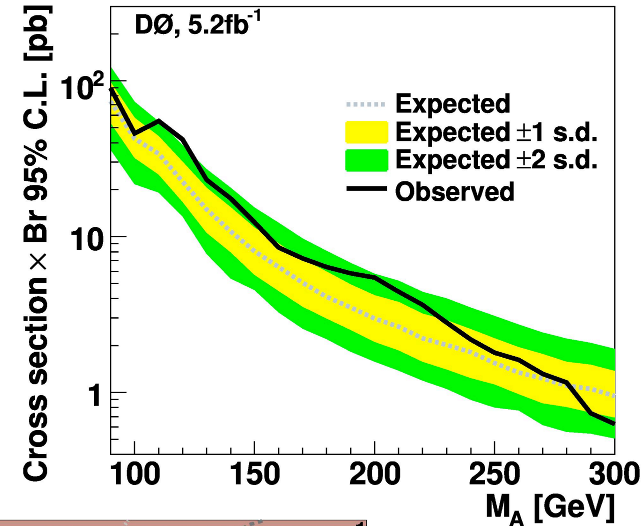


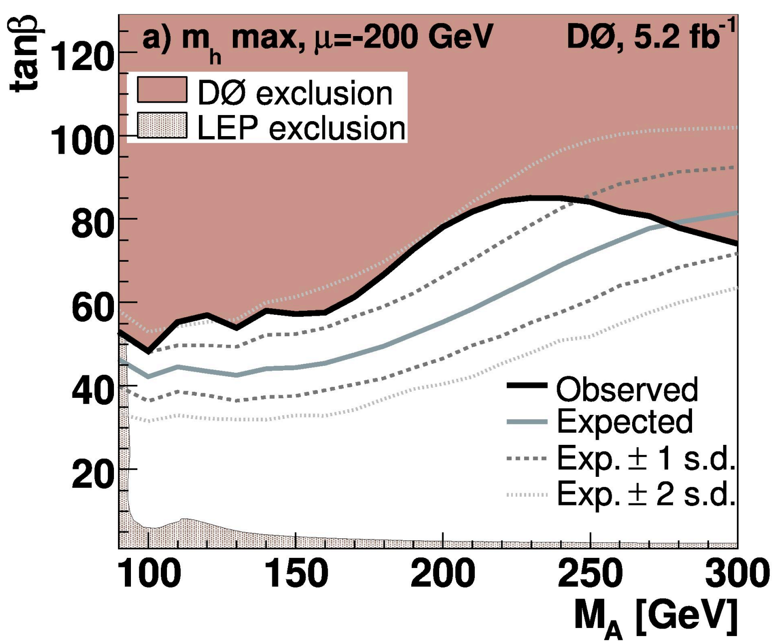
- Treat 3j, 4j samples separately to improve sensitivity
- Cut on a 6-variable likelihood to enhance S/B, separately for "low mass" (90-130 GeV) and "high mass" (130-300 GeV) regions of Higgs mass
- Use SHAPE of dijet invariant mass spectrum as final discriminating variable

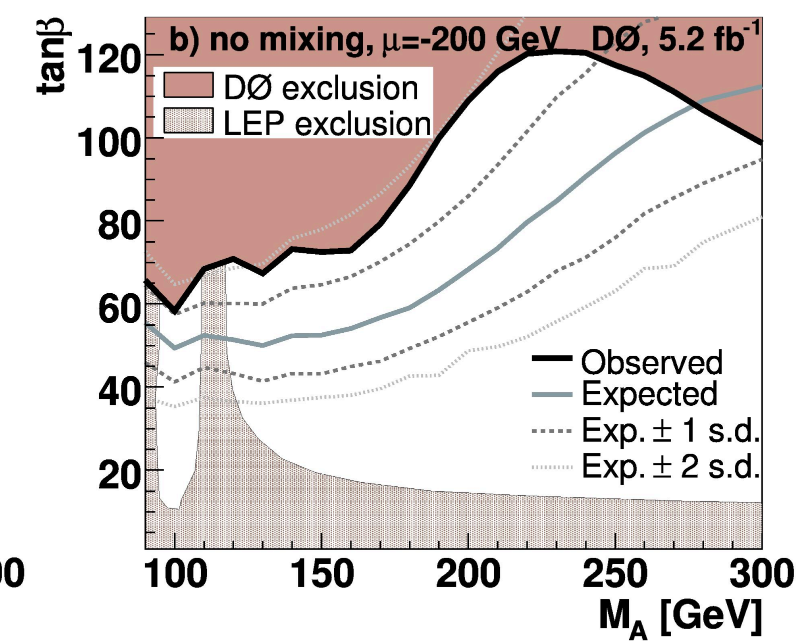
b+φ → bbb Results

- Most significant deviation seen, near 120 GeV, has a significance corresponding to ~ 2.0 sigma
  - Set model-independent limit on σ×BR
  - Result also interpreted in tanβ vs m_A plane of MSSM

[examine model dependence by evaluating in two different (“m_h max” and “no mixing”) scenarios]



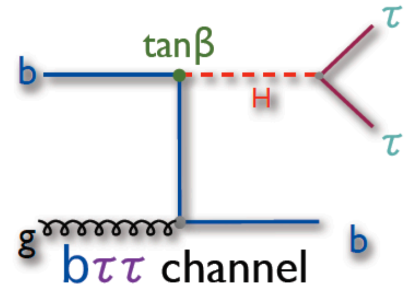


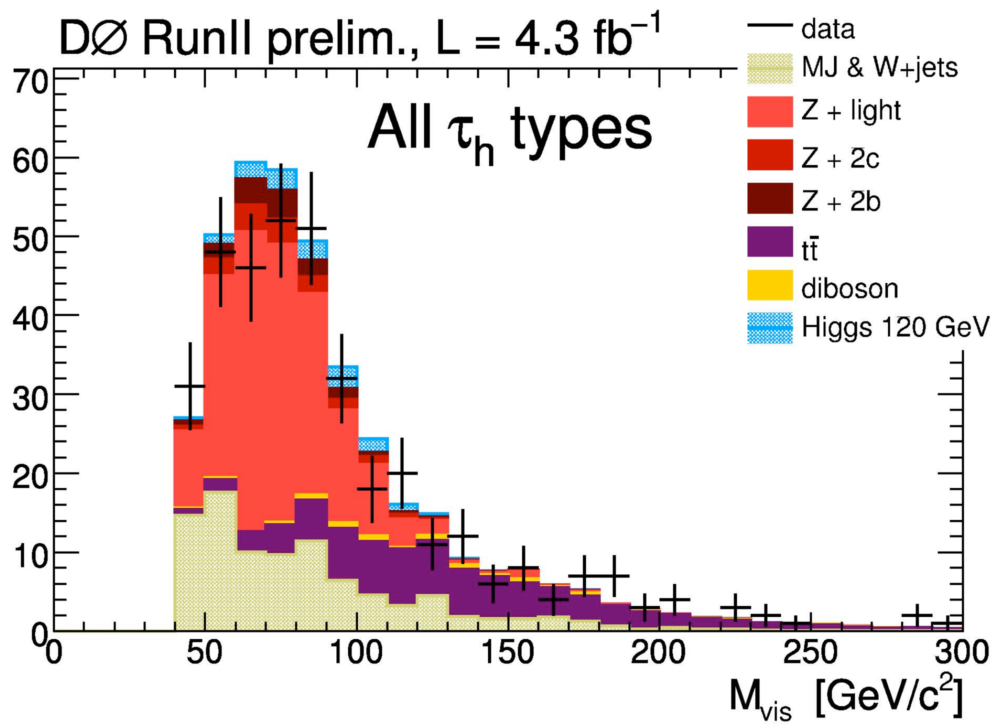


$b+\varphi \rightarrow b + \tau\tau$ ($\rightarrow b + \tau_\mu\tau_h$)

4.3 fb^{-1} (D0 6083-CONF) [update of 2.7 fb^{-1} result in PRL 104 (2010) 151801]

- **$b + \tau\tau$ mode has smaller BR than bbb, but less bkgnd**
  - **Also has less model dependence in MSSM interp.**
- **Compared to inclusive $\varphi \rightarrow \tau\tau$, $b+\tau\tau$ has greater sensitivity for low Higgs mass since b reduces bkgnd from $Z \rightarrow \tau\tau$**

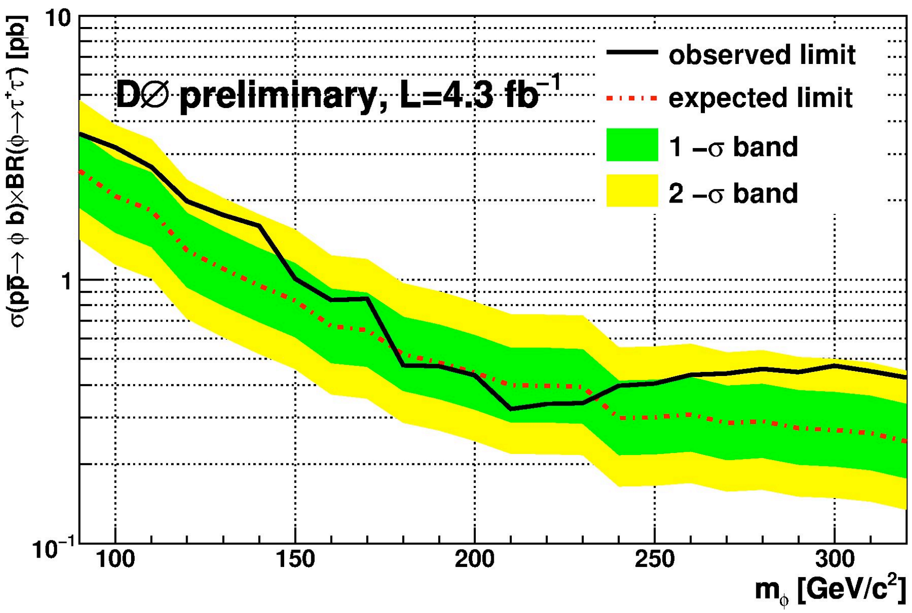


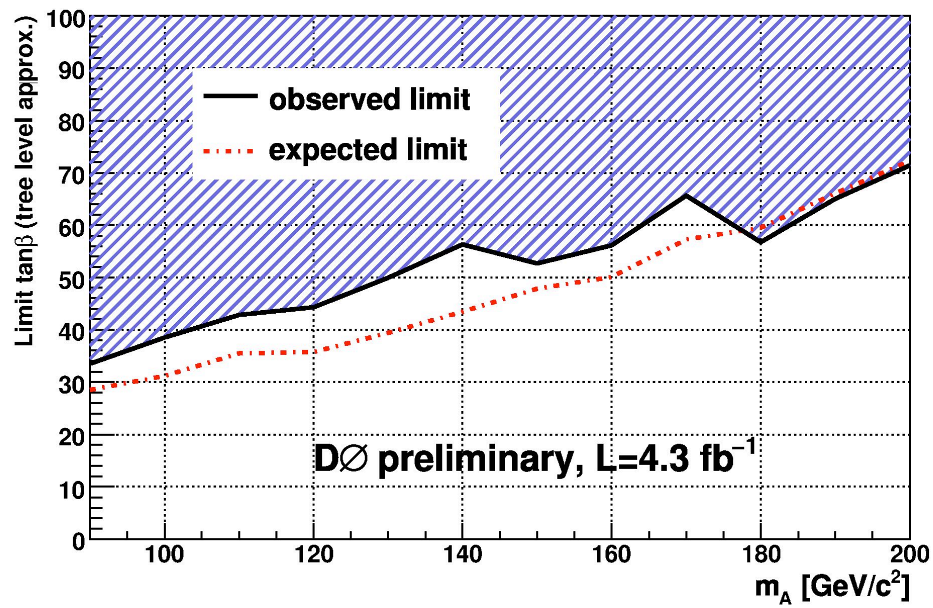


- **Calculate "visible mass" from muon, hadronic tau candidate and MET**
- **As final variable, use product of separate multivariate discriminants against t-tbar, multijet, and Z+jet bkgnds**

$b+\varphi \rightarrow b + \tau\tau$ ($\rightarrow b + \tau_\mu\tau_h$) Results

- No significant excess seen
  - Set model independent limit on $\sigma \times BR$
- Result also interpreted in MSSM
  - For low mA, reaching region of $\tan\beta < 35$ ($\sim m_t/m_b$)





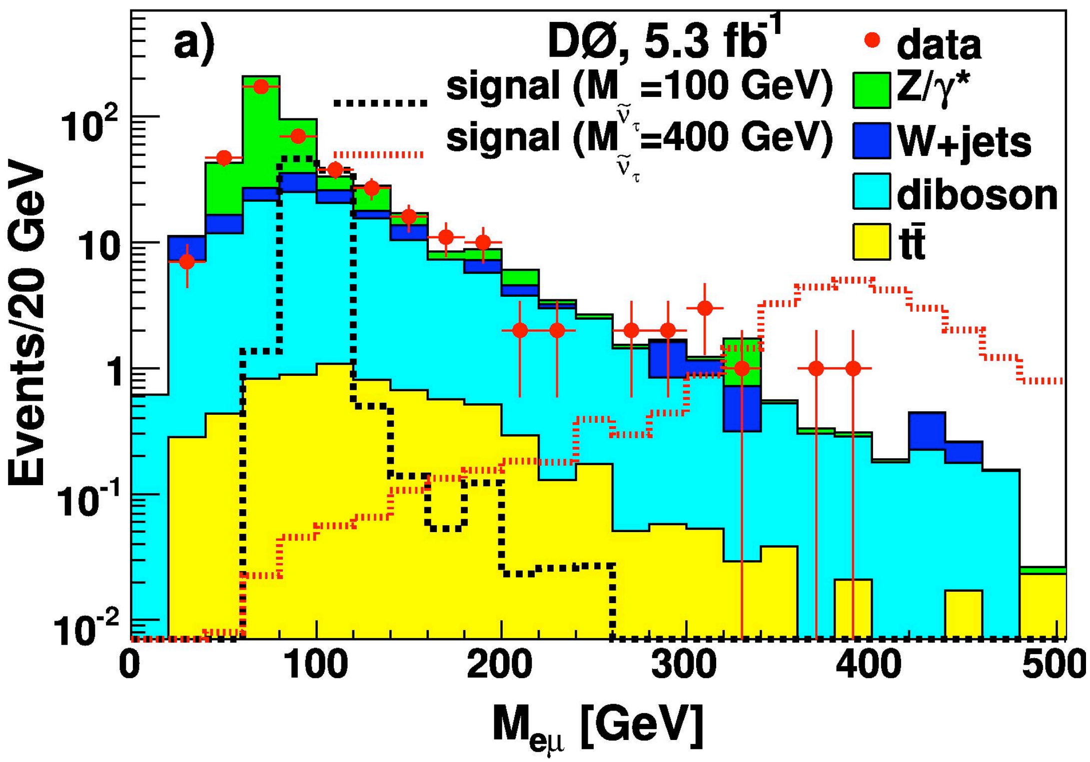
- Can combine with direct $\varphi \rightarrow \tau\tau$ (improves at higher m_A) and also with bbb
  - Last public combination was using only 1.2 fb^{-1} for $b\tau\tau$

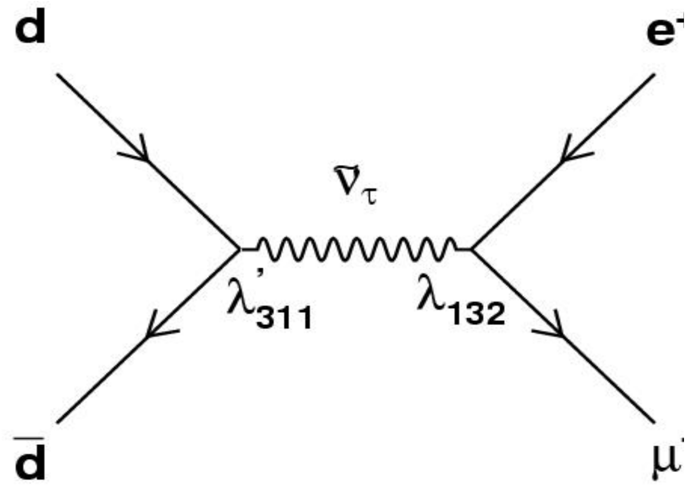
“Exotic” SUSY Searches

Sneutrino Search (with R-Parity Violation)

5.3 fb^{-1} [PRL 105 (2010) 191802]

- In case of RPV, can produce single sparticles
- Consider resonant tau sneutrino production, with dilepton decay
  - Search for peak in eμ invariant mass distribution

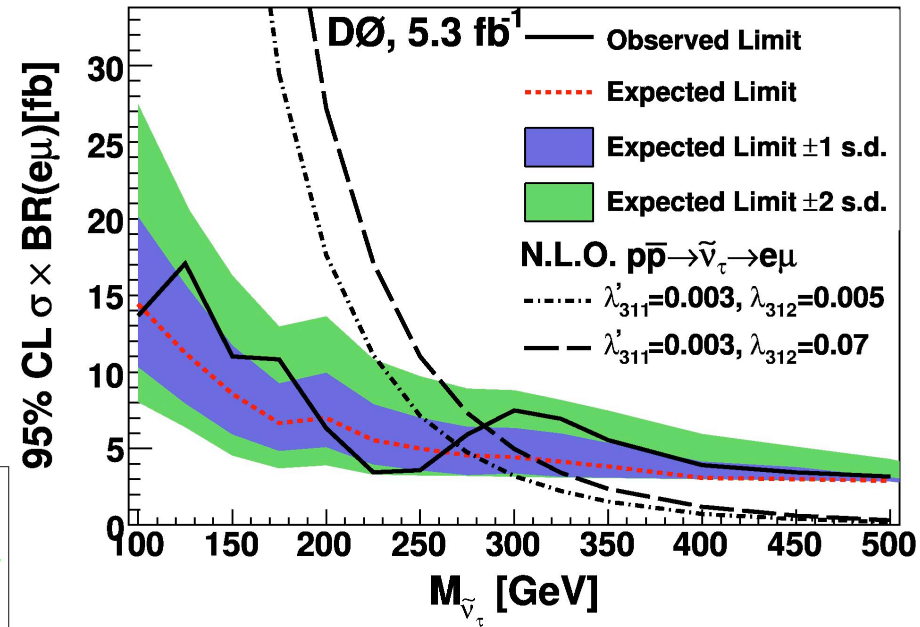


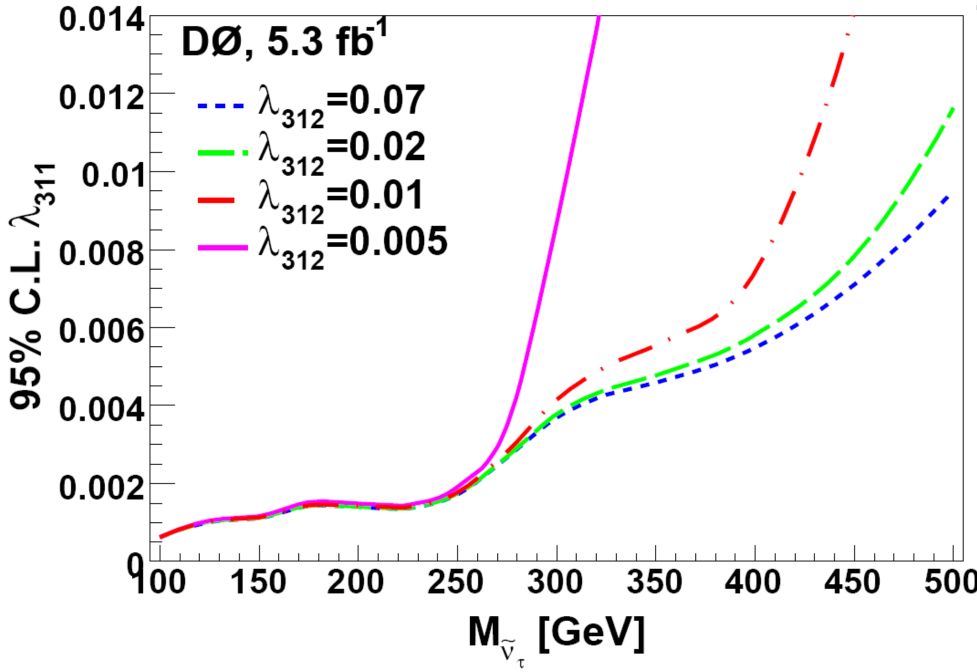


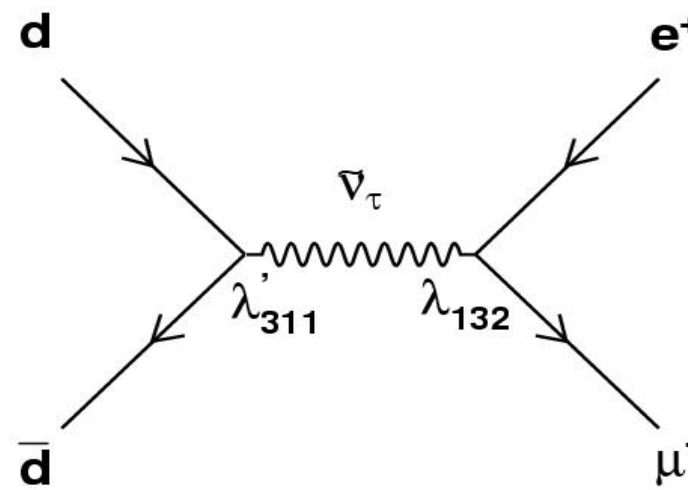
- SM bkgnd is mainly diboson production (for high eμ invariant mass) and Drell-Yan (for low mass)

Sneutrino Search (with RPV) Results

- No excess observed
- Can express limits as a function of sneutrino mass and the relevant RPV couplings

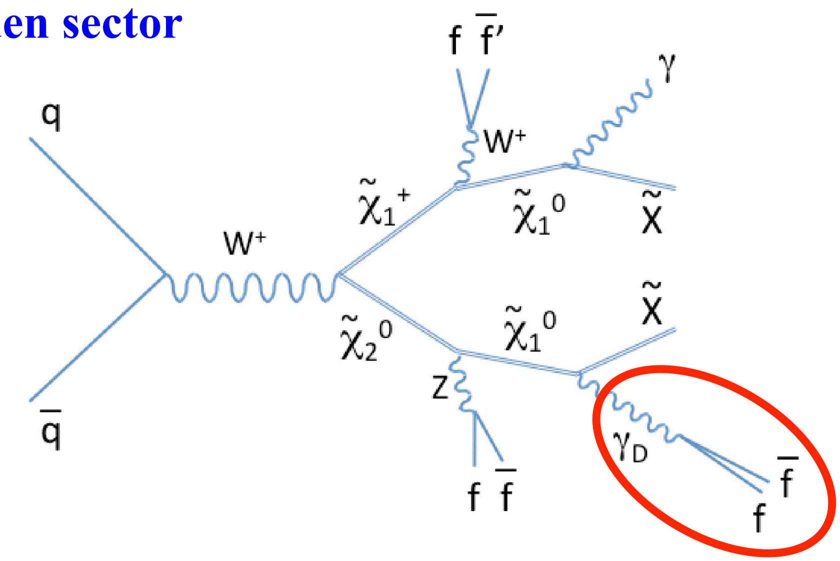






Hidden Valley Models with SUSY

- Hidden valley models propose a hidden sector that is very weakly coupled to SM particles
  - motivated (in part) by some astrophysical anomalies
- Force carrier in hidden sector, “dark photon” (γ_D), decays (via mixing with photon) to SM fermion pairs
  - given low γ_D mass, its decay products would be close together in detector
- If HV model includes SUSY, have SUSY partners of both SM and HV particles
- Could have gaugino pair production, with cascade decays to SUSY LSP (neutralino), followed by LSP decays to hidden sector
  - photon + dark LSP ($\tilde{X}$)
  - dark photon (γ_D) + dark LSP ($\tilde{X}$)
- Search for events with MET and one or more “lepton jets”
  - Lepton (e/μ) matched to track, together with a companion track of opposite charge within $\Delta R = 0.2$

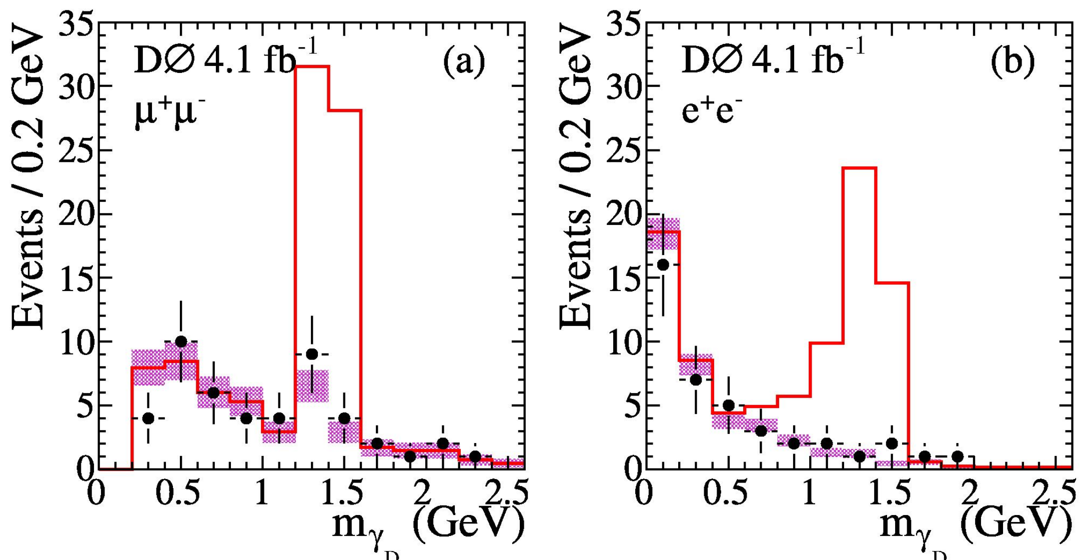


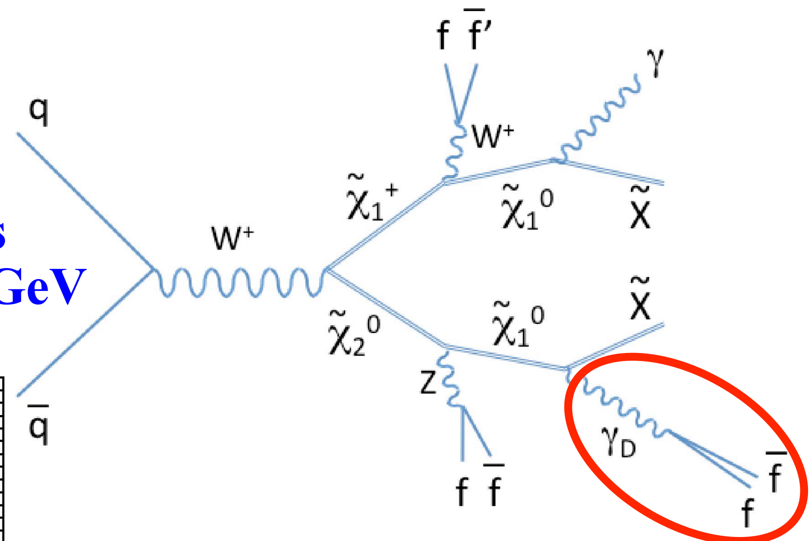
HV: Search for Single Lepton Jet

Search for γ + MET + 1 "lepton jet"

4.1 fb^{-1} [PRL 103 (2009) 081802]

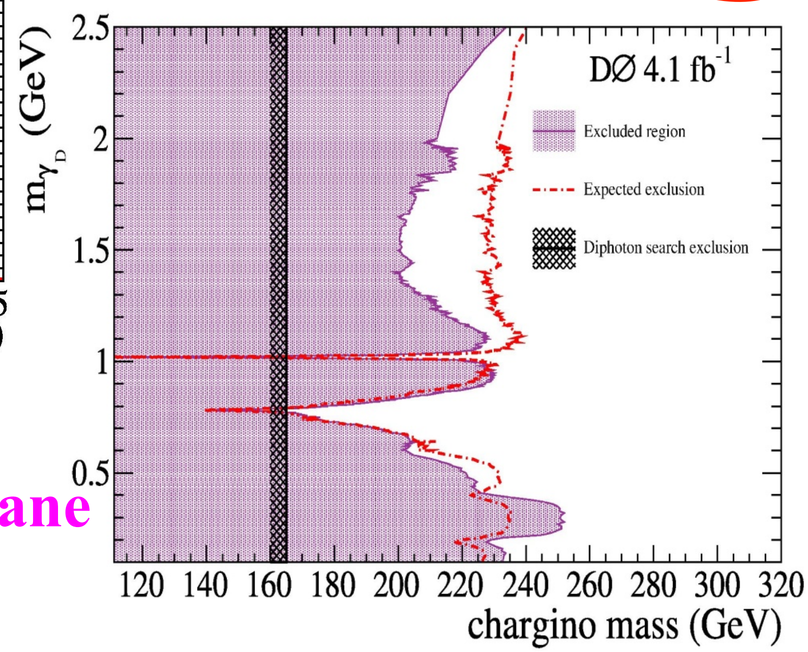
- **Look for excess of low mass dilepton pairs in events with a high E_T γ and MET > 20 GeV**





Red histograms show signal dist'ns for m(γ_D) = 1.4 GeV

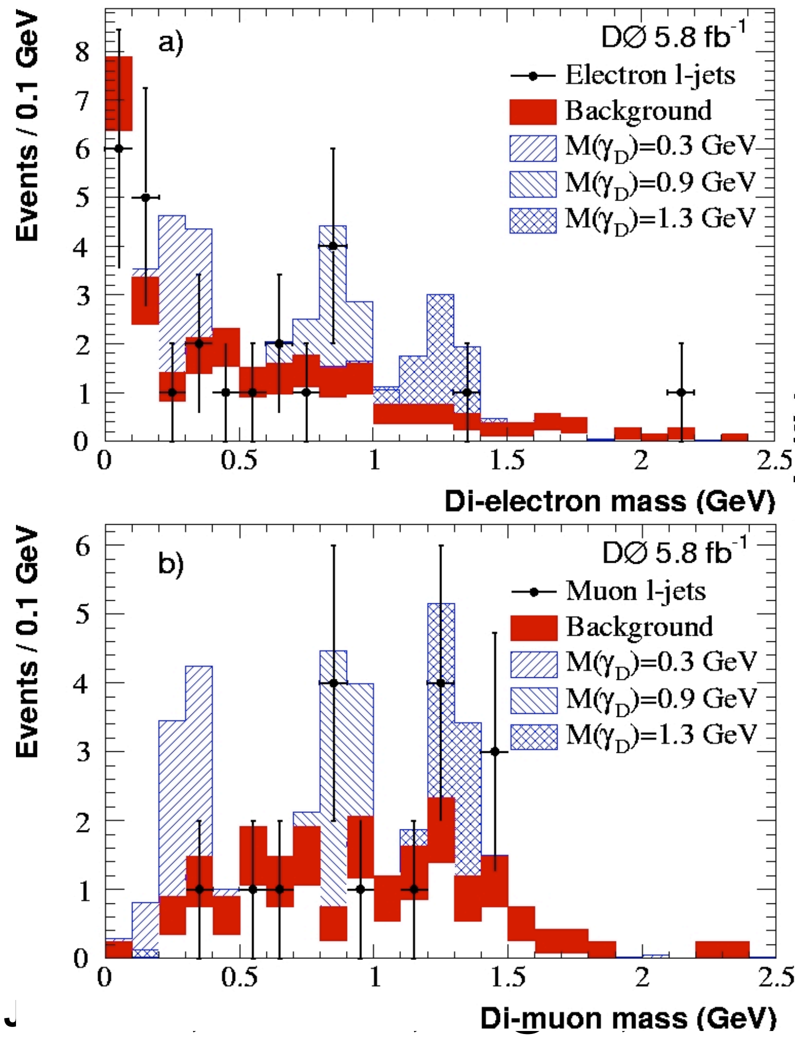
Limits set in m(γ_D) vs m($\chi^{\pm}$) plane

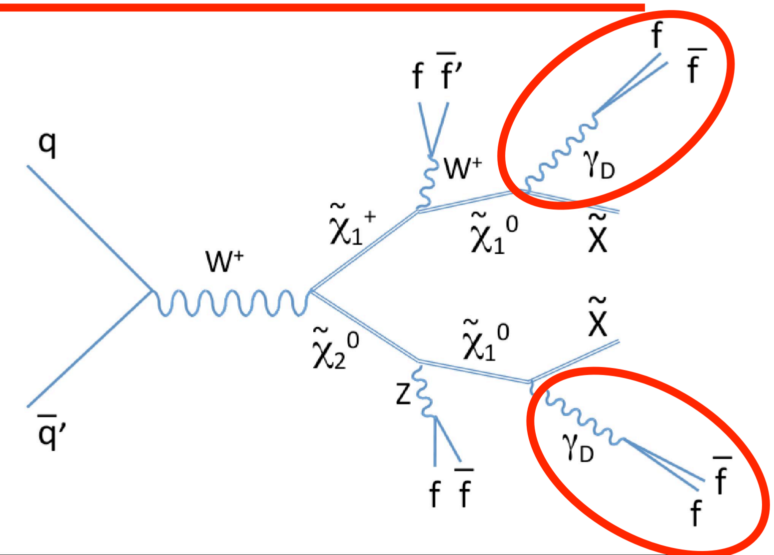


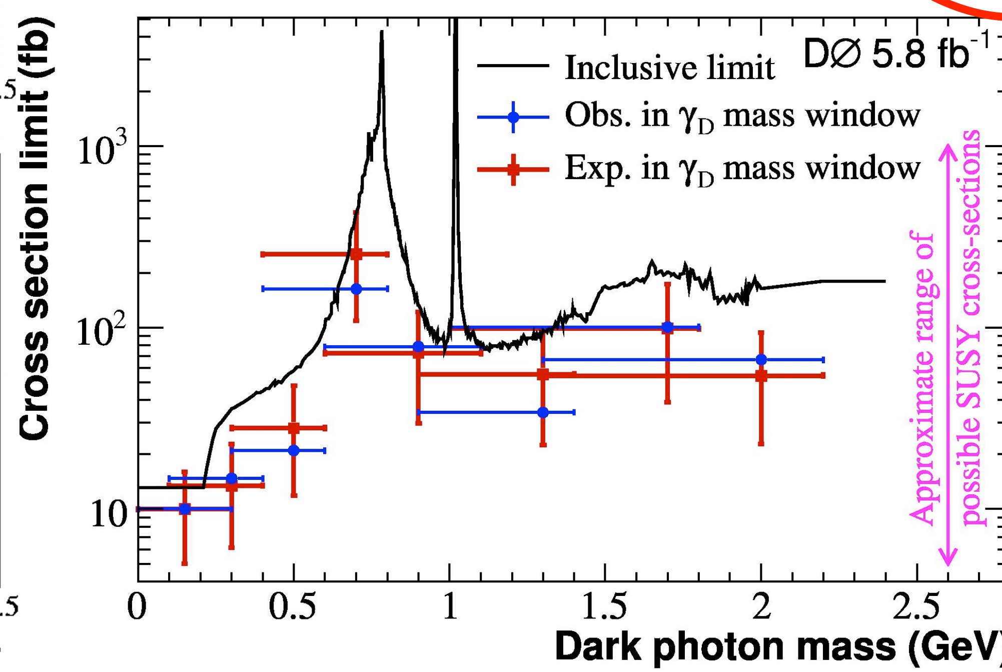
HV: Search for Lepton Jet Pair

Search for MET + 2 "lepton jets"

5.8 fb^{-1} [PRL 105 (2010) 211802]



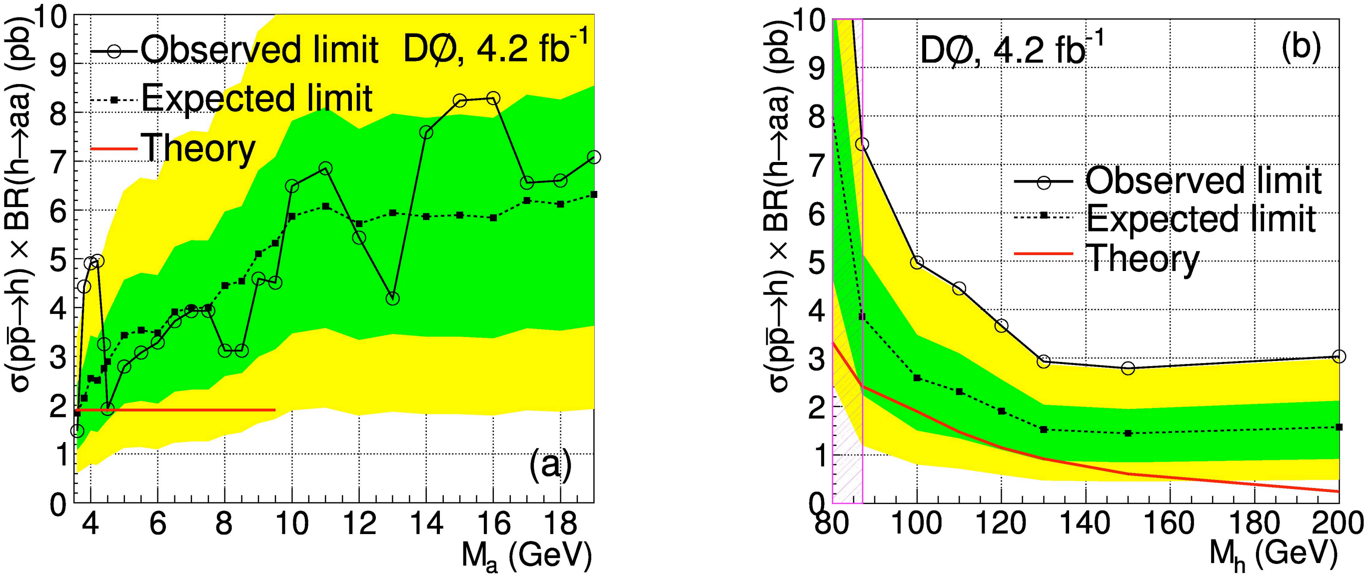




NMSSM Higgs h→aa

4.2 fb^{-1} [PRL 103 (2009) 061801]

- **Non-observation of Higgs below ~114 GeV seriously constrains MSSM**
- **Next-to-MSSM can reduce this tension, due to reduction of BR(h→bb) because of h→aa decay (where a is a LIGHT Higgs pseudoscalar)**
  - **For low m_a, expect a decays to muon or tau pairs**
  - **Analysis considered h→aa→μμμμ or μμττ**
- **No signal seen, and limits set as a function of m_a and m_h**

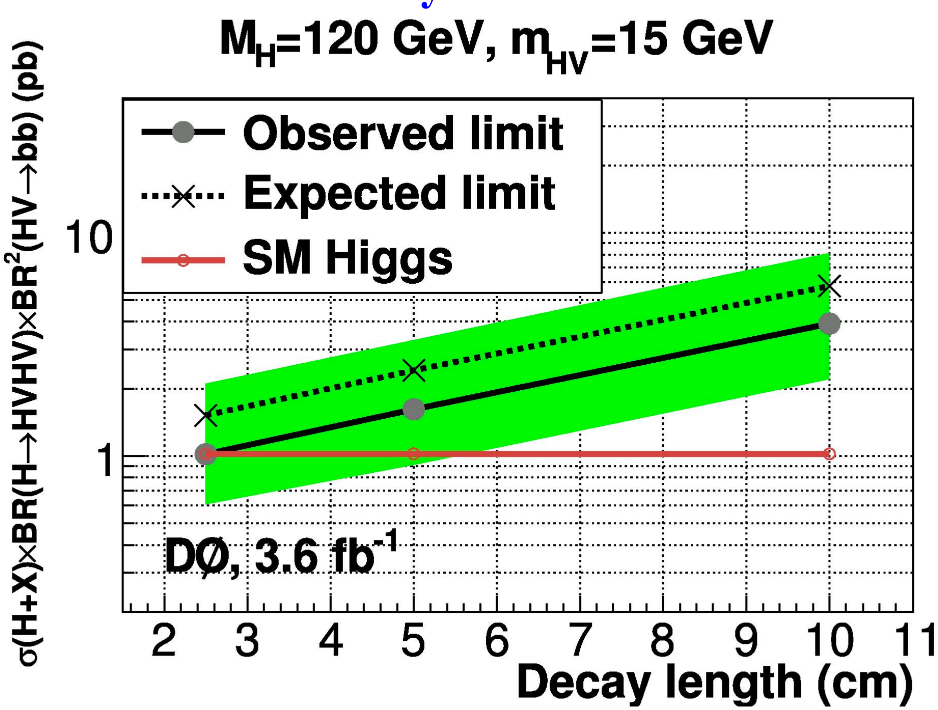


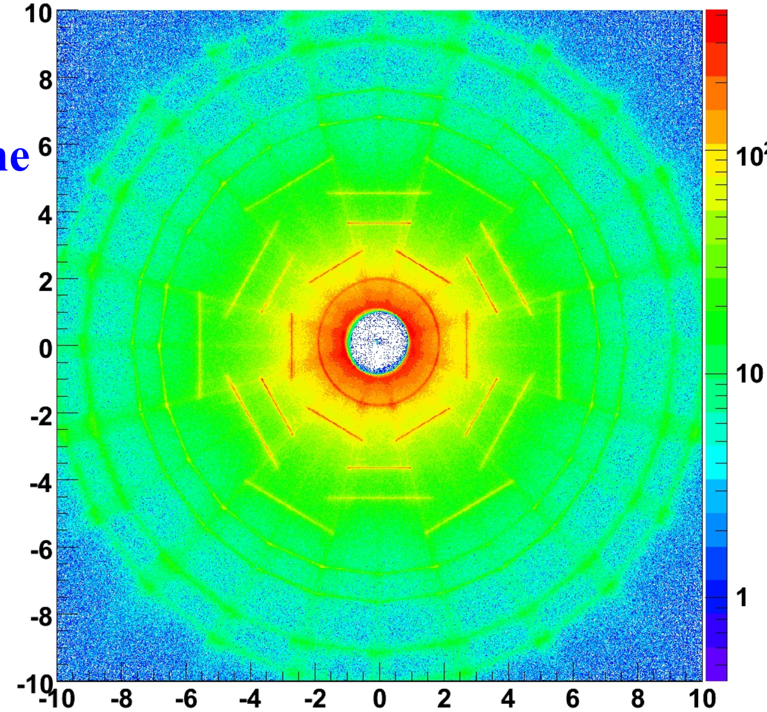
One More HV-Motivated Search

Search for pair production of long-lived particles decaying to b b-bar

3.6 fb^{-1} [PRL 103 (2009) 071801]

- **Look for pairs of displaced vertices, with Ntrk ≥4, in tracker at radii 1.6 – 20 cm from beamline**
- **Avoid regions of high material density**
- **Further cuts to enhance S/B include SV mass and collinearity**





- **No excess seen about bkgnd expectation**
  - **Limits set**

Summary and Outlook

- D0 has searched for SUSY in a variety of final states and signatures
  - Most recent analyses utilize > 3 fb^{-1} (even up to 6.3 fb^{-1})
  - So far, no evidence for SUSY observed, and limits set on a variety of SUSY models

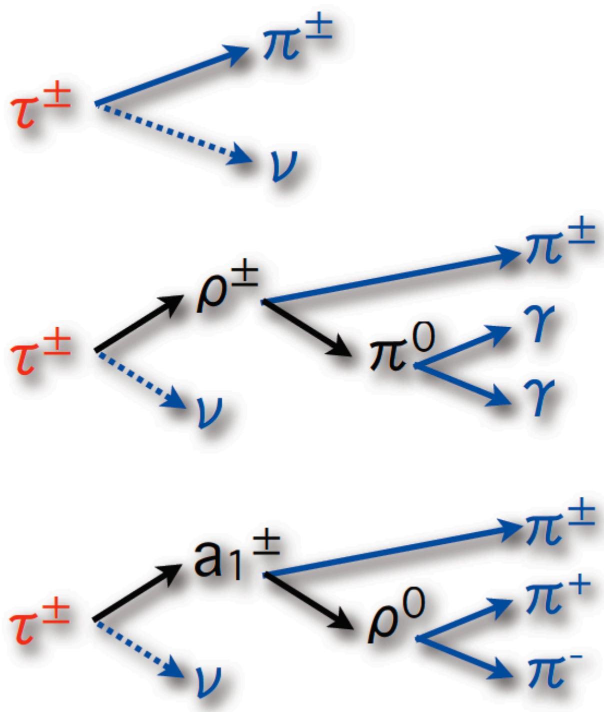
- In addition to performing “classic” SUSY searches, D0 has pioneered many searches for more “exotic” experimental SUSY signatures

- Tevatron has delivered ~ 10 fb^{-1} in Run II, and is currently approved to run through fall 2011 (expect to reach ~ 12 fb^{-1} delivered)
  - Achieved instantaneous luminosity as high as 4E32
  - Typically integrating > 50 pb^{-1}/week

- LHC SUSY results are starting to appear
  - Increased energy should allow LHC experiments to surpass Tevatron results, even with limited integrated luminosity, in “classic” SUSY searches
  - Sophistication of detector understanding and SM physics measurements at Tevatron, might give Tevatron a somewhat longer lead time for more “exotic” SUSY searches

Backup Slides

D0 Reconstruction of Hadronic τ Decays



type 1:
trk + cal
(no EM cluster)

type 2:
trk + cal
(with EM cluster)

type 3:
> 1 trk**s** + cal

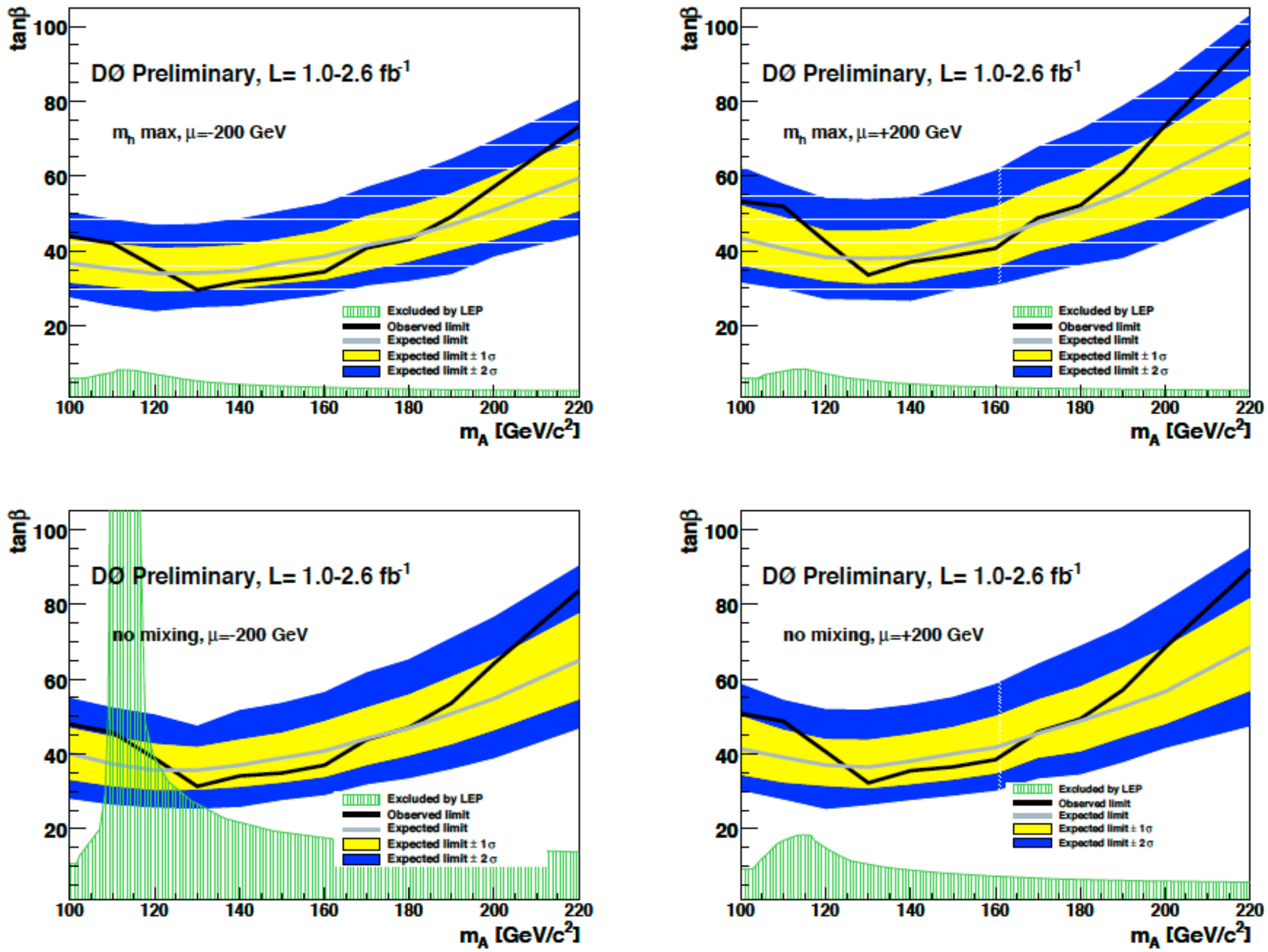
NN_τ based on isolation, shower shape, trk-cal consistency variables

NN_τ performances (not including τ-reco efficiency) @ DØ

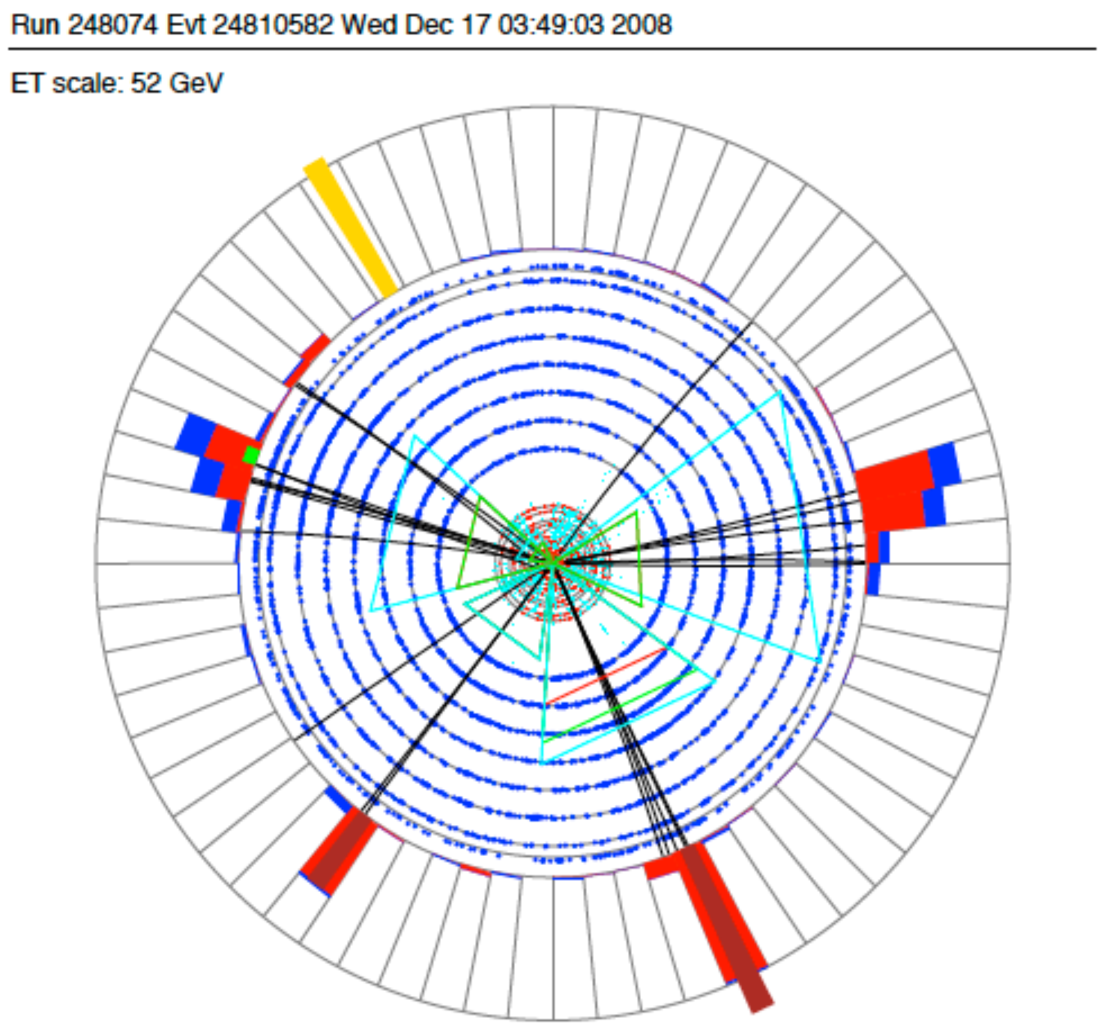
- efficiency (τ leptons): 60/75/65 %
- fake rate (light jets): 3.0/2.5/2.5 %

(Summer 09) D0 MSSM Neutral Higgs Combination

- Combine results from b+bb, b+ττ, and direct φ→ ττ
  - Last public result uses 2.6 fb^{-1}, 1.2 fb^{-1}, and 2.2 fb^{-1}, respectively



Event Display of Event with 2 e-jet Candidates



XY view of a two electron l-jet candidate event in data with large $\not{E}_T$.

MSSM Benchmark Scenarios

- **For neutral Higgs searches: $\sigma \times$ BR limits $\Rightarrow$ interpreted in MSSM**
- **Tree-level: Higgs sector of MSSM described by m_A & $\tan\beta$**
  - radiative corrections introduce dependence on additional SUSY parameters
- **Five additional, relevant parameters**
  - M_{SUSY} Common Scalar mass: parameterizes squark, gaugino masses
  - X_t Mixing Parameter: related to the trilinear coupling $a_t \rightarrow$ stop mixing
  - M_2 SU(2) gaugino mass term
  - μ Higgs mass parameter (where $\Delta_b \propto \mu \times \tan\beta$)
  - $m_{\tilde{g}}$ gluino mass: comes in via loops
- **Two common benchmarks**
  - m_h^{max} (max-mixing): Higgs boson mass, m_h, close to maximum possible value for a given $\tan\beta$
  - no-mixing: vanishing mixing in stop sector $\Rightarrow$ small Higgs boson mass, m_h

Constrained Model: Unification of SU(2) and U(1) gaugino masses

	m_h^{max}	no-mixing
M_{SUSY}	1 TeV	2 TeV
X_t	2 TeV	0
M_2	200 GeV	200 GeV
μ	±200 GeV	±200 GeV
$m_{\tilde{g}}$	800 GeV	1600 GeV

Charged massive long-lived particles

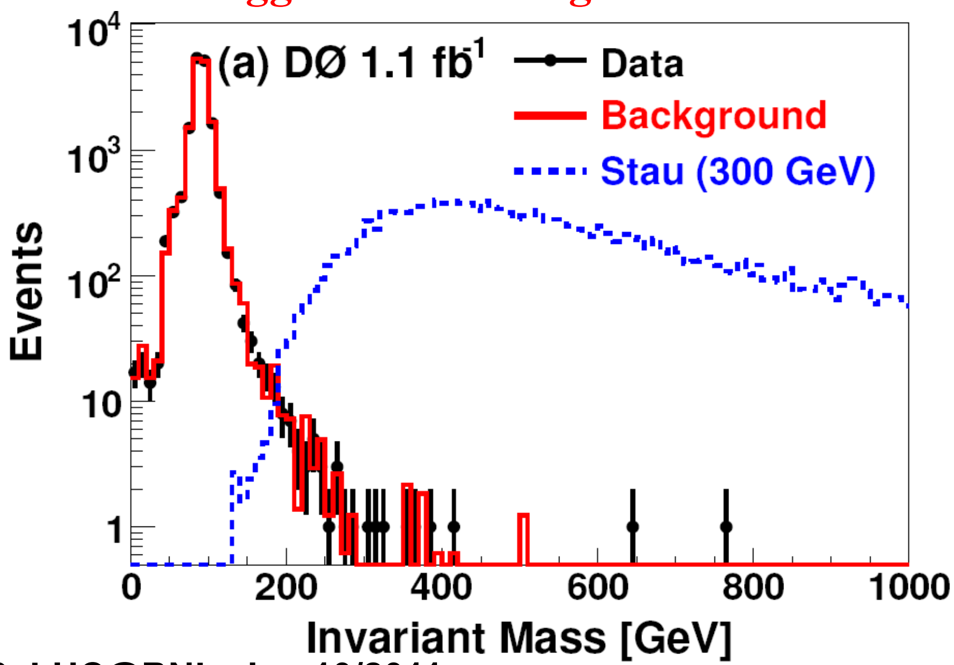
- **Various SUSY variants predict the existence of long-lived charged particles**
  - **Look like highly-ionizing “slow muons” in the detectors**
  - **Use time-of-flight information to determine mass**

(1.1 fb^{-1}) [PRL 102 (2009) 161802]

- **Interpret as limits on stable stau production, or**

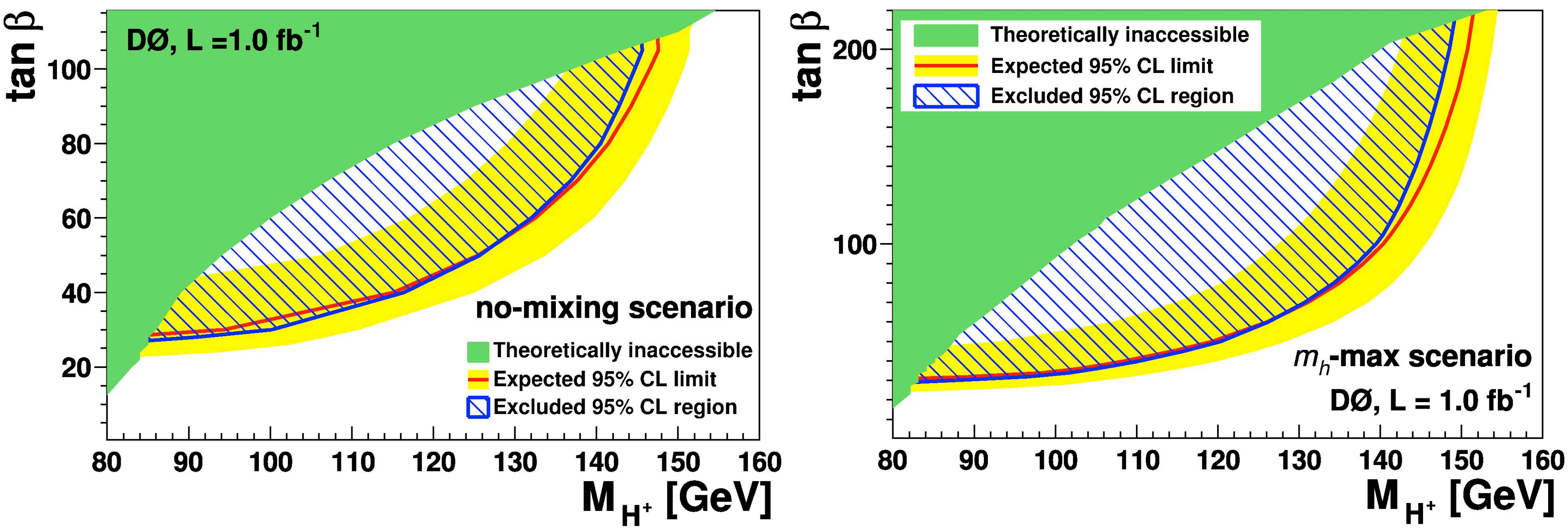
  m > 206 GeV for gaugino-like chargino, or

  m > 171 GeV for Higgsino-like chargino



Charged Higgs Search

1.0 fb^{-1} [PLB 682 (2009) 278]

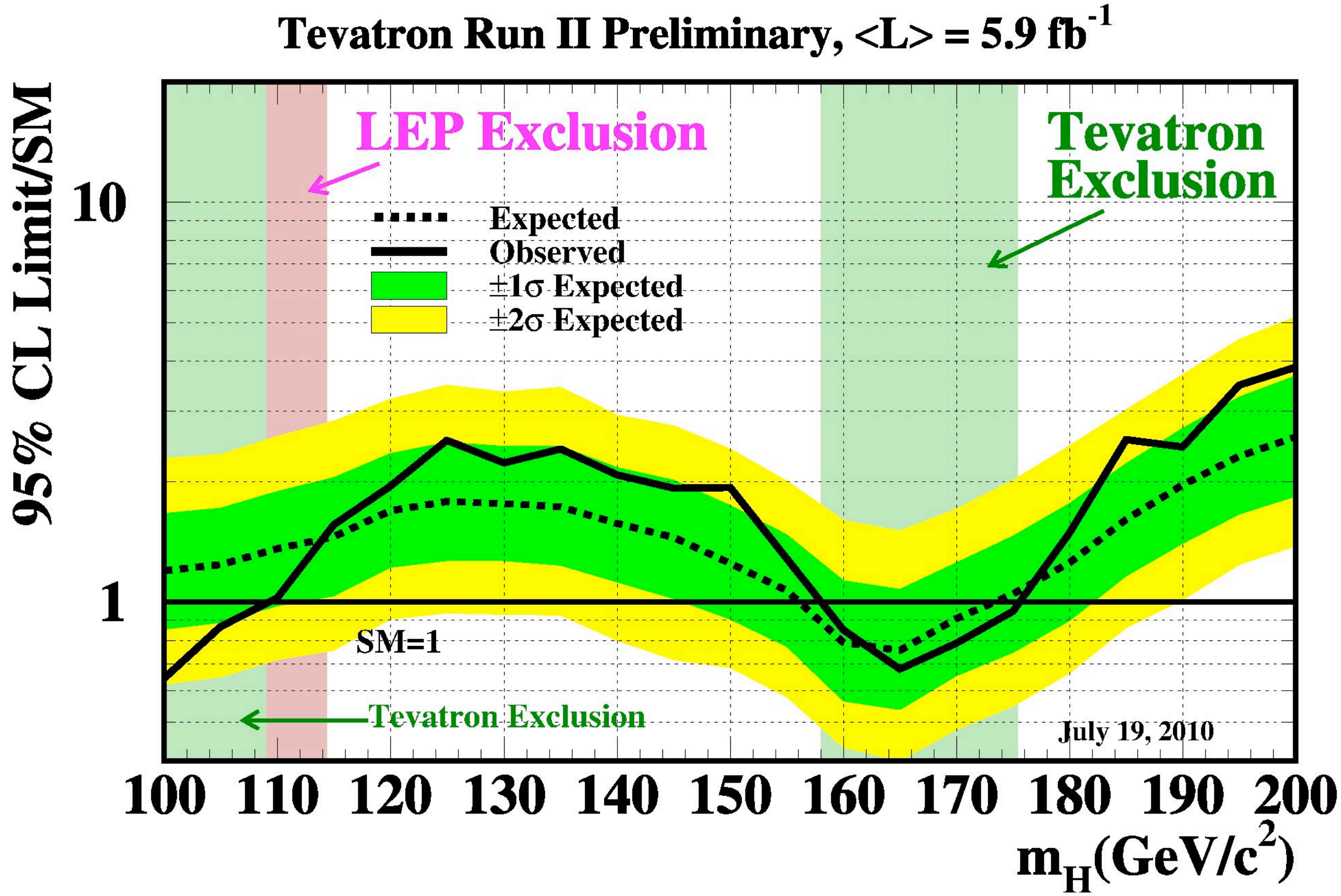


Latest (ICHEP'10) Tevatron SM Higgs Combination

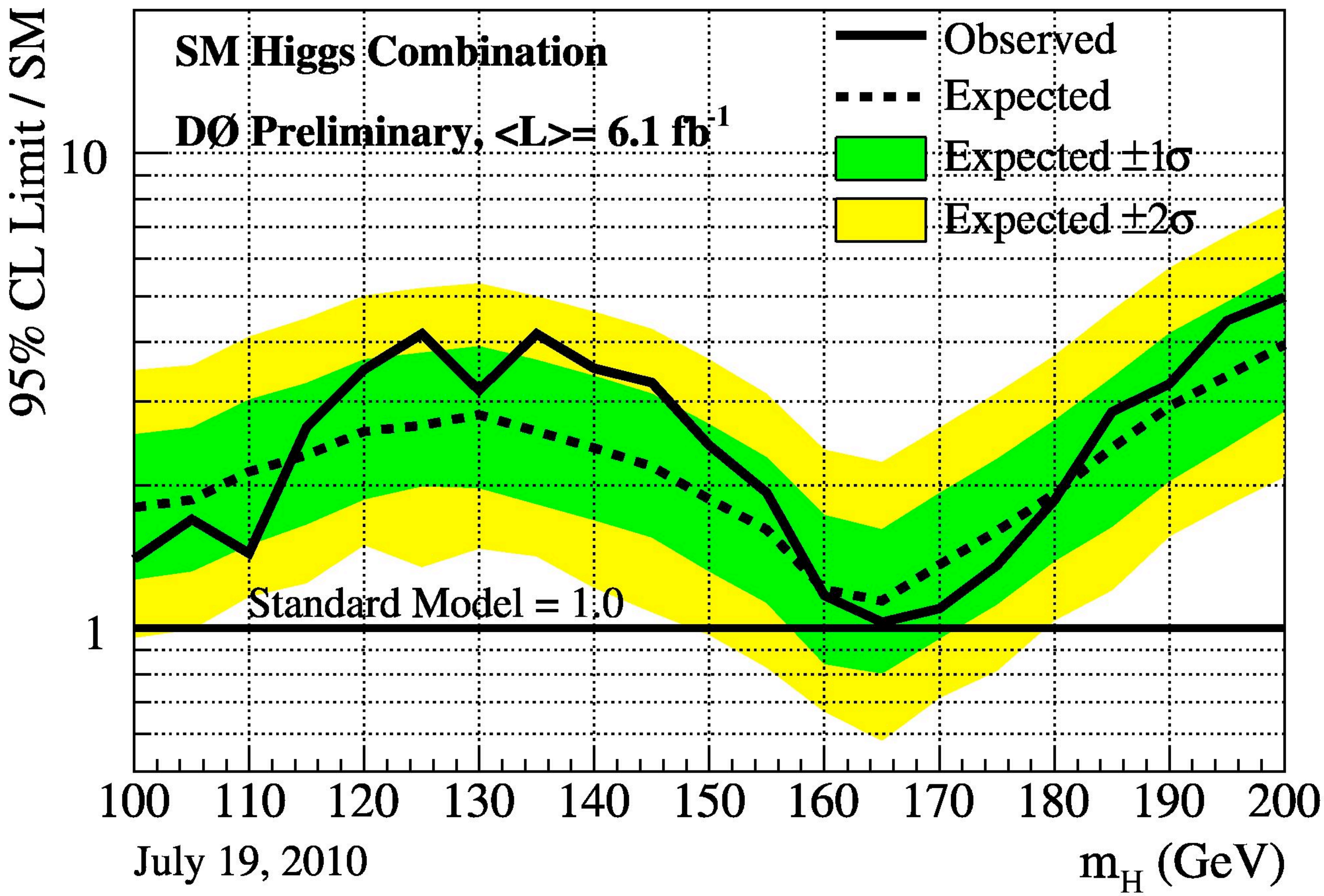
- Using up to 6.7 fb^{-1}, the Tevatron experiments combined exclude (@ 95% CL),

  158 GeV < m(H) < 175 GeV

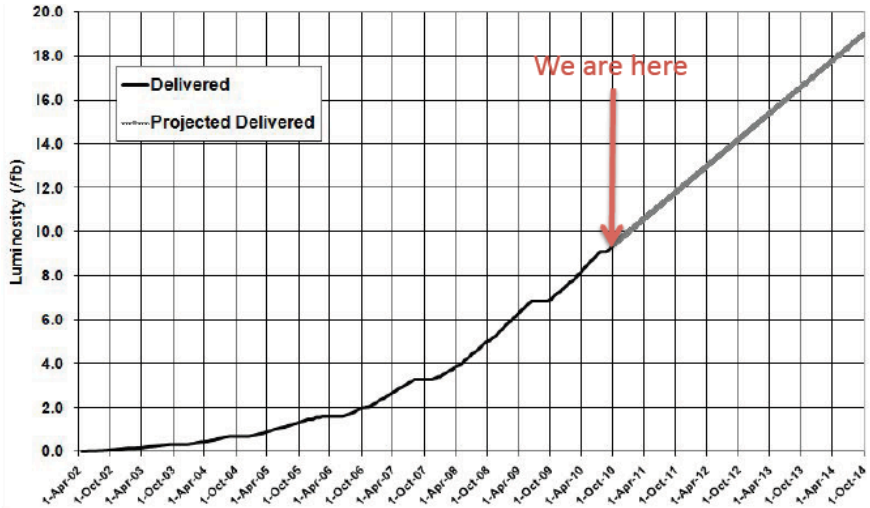
(and m(H) in the range [100, 109] GeV)



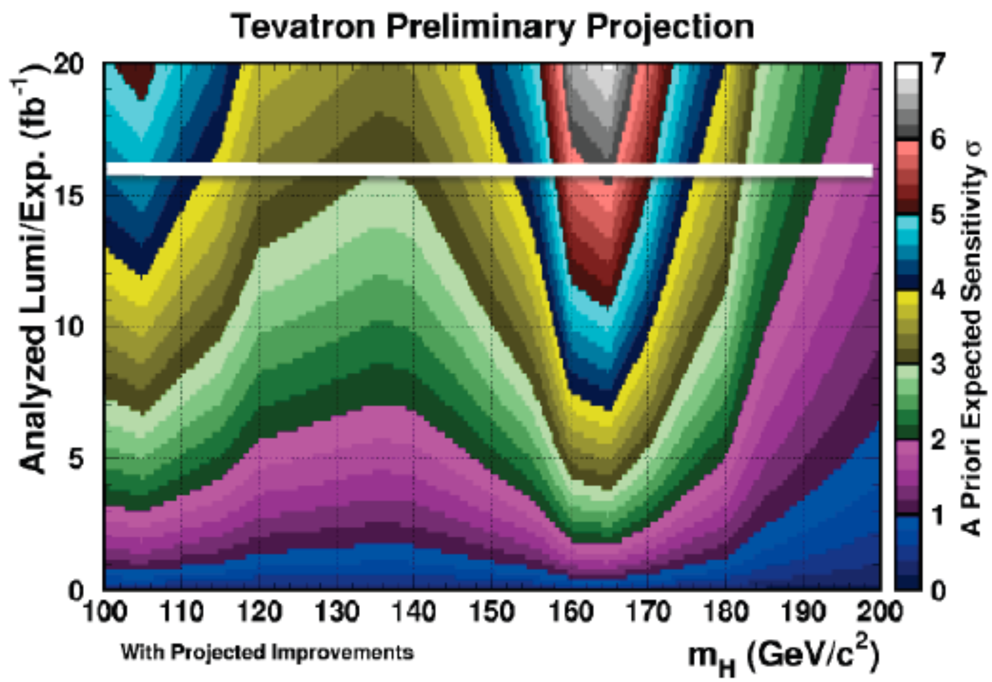
Latest (ICHEP'10) D0 SM Higgs Combination



Possible 3 Year Extension of Tevatron Run?



- With 3 year extension of run, would expect to reach ~ 19 fb^{-1} delivered
  - ~ 16 fb^{-1} / experiment analyzable
- Could reach at least 3 sigma evidence, or exclusion, of SM Higgs boson over favored range up to 190 GeV



- HEPAP P5 subpanel supported proposed extension, if required additional funding is available
  - FNAL has requested additional funds from DoE and is awaiting response